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**AUTOMATION OF CLOSED ENVIRONMENTS IN
SPACE FOR HUMAN COMFORT AND
SAFETY**

REPORT

FOR

ACADEMIC YEAR 1989-90

BY

**Kansas State University
College of Engineering
Departments of Mechanical Engineering, Chemical Engineering,
Industrial Engineering, and Electrical and Computer Engineering**

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Submitted to

**NASA/USRA
ADVANCED DESIGN PROGRAM**

ABSTRACT

This report presents the results of the first year of a three year project on the automation of the Environmental Control and Life Support System (ECLSS) of the Space Station Freedom (SSF). The results are applicable to other future space mission. The work was done by the Kansas State University NASA/USRA interdisciplinary student design team. The report begins with a discussion of the six ECLSS subsystems and how they interact. Proposed control schemes and their rationale are discussed for the Atmosphere Revitalization (AR) subsystem. Finally, a description of the mathematical models for many components of the ECLSS control system concludes the report.

TABLE OF CONTENTS

	page
1.0 INTRODUCTION	1
1.1 Project Description	2
1.2 Organization of the Document	3
2.0 APPROACH	4
2.1 Design Team Description	5
2.2 Three Phase Plan	6
3.0 PHYSICAL DESCRIPTION	7
3.1 Air Revitalization Subsystem	8
3.1.1 Carbon Dioxide Removal	8
3.1.2 Carbon Dioxide Reduction	11
3.1.3 Oxygen Generation	15
3.2 Temperature and Humidity Control Subsystem	18
3.3 Water Recovery and Management Subsystem	24
3.4 Waste Management Subsystem	27
3.5 Fire Detection and Suppression Subsystem	30
3.6 Atmospheric Control and Supply Subsystem	34
4.0 CONCEPTUAL CONTROL	37
4.1 Carbon Dioxide Removal	38
4.2 Carbon Dioxide Reduction	43
4.3 Oxygen Generation	47
5.0 Math Models	51
5.1 Carbon Dioxide Removal	52
5.2 Carbon Dioxide Reduction	81
5.3 Oxygen Generation.	93
6.0 APPENDICES	108
A. Cited References	109
B. References	111
C. Acronyms	115

LIST OF FIGURES

Figure	page
3.1-1 AR Block Diagram	8
3.1-2 Four Bed Molecular Sieve	9
3.1-3 Carbon Dioxide Reduction System	11
3.1-4 Oxygen Generation Assembly	15
3.1-5 Electrolysis Cell	16
3.2-1 THC Block Diagram	18
3.2-2 THC with AR, WRM and FDS	19
3.2-3 Temperature and Humidity Ventilation Control	20
3.2-4 Dual-Fluid, Counterflow Heat Exchanger.	20
3.2-5 Slurper	21
3.2-6 Avionics Air Cooling	22
3.2-7 Thermally Conditioned Storage	22
3.3-1 WRM Block Diagram	24
3.4-1 WM Block Diagram	27
3.5-1 FDS Block Diagram	30
3.6-1 ACS Block Diagram	34
4.1-1 Four-Bed Operation as a Function of Time	39
4.1-2 Proposed Carbon Dioxide Removal Sensor Locations.	42
4.2-1 Proposed Carbon Dioxide Reduction Sensor Locations.	44
4.3-1 Proposed OGA Sensor Locations	49
5.1-1 Modeled Carbon Dioxide Removal Bed.	52
5.1-2 Regenerator (Preheater)	72
5.2-1 Mass Balance Diagram	82
5.2-2 Schematic Diagram for Energy Balance.	83
5.2-3 Regenerator Heat Transfer Diagram	89
5.3-1 Oxygen Generation Assembly System Notation.	93
5.3-2 Water Tank Schematic	94

LIST OF TABLES

Table	page
4.1-1 Carbon Dioxide Operating Modes.	40
4.3-1 OGA Performance Requirements	47

1.0 INTRODUCTION

1.1 PROJECT DESCRIPTION

The Environmental Control and Life Support System (ECLSS) for the proposed Space Station Freedom presents many new challenges for present technologies. Current plans call for a crew of eight to live in a safe, shirt-sleeve environment for 90 days without ground support. Because of these requirements, all life support systems must be self-sufficient and reliable.

The ECLSS is composed of six subsystems. The Temperature and Humidity Control (THC) subsystem maintains the cabin temperature and humidity at a comfortable level. The Atmosphere Control and Supply (ACS) subsystem insures proper cabin pressure and partial pressures of oxygen and nitrogen. To protect the space station from fire damage, the Fire Detection and Suppression (FDS) subsystem provides fire sensing alarms and extinguishers. The Waste Management (WM) subsystem compacts solid wastes for return to earth, and collects urine for water recovery.

Because it is impractical, if not impossible, to supply the station with enough fresh air and water for a 90 day mission, these elements are recycled. The Air Revitalization (AR) subsystem removes CO₂ and other dangerous contaminants from the air. The CO₂ is then broken down into solid carbon and oxygen. The Water Recovery and Management (WRM) subsystem collects and filters condensate from the cabin to replenish potable water supplies and processes urine and other waste waters to replenish hygiene water supplies.

These subsystems are not fully automated at this time. Furthermore, the control of these subsystems is not presently integrated, i.e., they operate independently of one another. In fact, if the station were to be operated at its present state of development, the astronauts would be required to spend a significant amount of time monitoring and adjusting the system. An astronaut's time is too valuable to be spent watching gages and adjusting valves. In addition, possible human error or slow reaction time could cause unnecessary risk to the crew or station if the crew is solely responsible for constant control of the ECLSS. Consequently, ECLSS automation and control is urgently needed for space travel and habitation.

1.2 ORGANIZATION OF THE DOCUMENT

This paper is the formal progress report for the Kansas State University NASA/USRA Advanced Design Team. The purpose of this report is to present a compilation of our research and project activities from September 1, 1989 through June 1, 1990. The report summarizes each subsystem within the ECLS system and provides detail of our advances towards the control and automation of the entire ECLSS. Because of the large number of acronyms in the paper, the reader may find it helpful to reference the acronym list in Appendix C.

2.0 DESIGN APPROACH

2.1 DESIGN TEAM DESCRIPTION

The KSU Advanced Design Team is composed of engineering students from several disciplines, a student from general science and education, a graduate student assistant, and engineering faculty members. Chemical, electrical, industrial, and mechanical engineering disciplines are represented by both students and faculty.

To complete the first semester's work, the design team appointed three lead engineers to work with faculty and the GTA to organize and direct the activities of the group. Initial breakdown of the group assigned two or three students to each subsystem to collect information. Once the preliminary investigation had taken place, the AR subsystem was selected for further study.

During the second semester, the design team was organized into three groups to study the AR subsystem in detail. One group focused on mathematical models, another group studied control strategies while the third concentrated on physical operations.

2.2 THREE PHASE DESIGN PLAN

The Kansas State University Advanced Design Team has finished the first year of a three year project which involves researching and designing controls for automation of the ECLSS for Space Station Freedom and other planned space operations. The chosen approach to solve this problem is to divide the design into three phases. The first phase is to research the ECLSS as a whole and then concentrate efforts on the automation of a single subsystem. The atmosphere revitalization (AR) subsystem was chosen for our focus. The system control design process will then be applied to each individual subsystem in the second phase. Finally, phase three will involve the final development of the entire ECLSS automation and control. To aid in the development of automatic controls for each subsystem and the overall ECLSS, mathematical models are being used for system simulation. Once the simulation has been completed, various methods of control can be tested.

The KSU Design Team has completed phase one and is currently in the midst of phase two. Mathematical models have been developed and numerous AR subassembly components have been simulated in an effort to develop efficient control schemes as well as a better understanding of how the subassemblies behave. Phase two development is forecasted to continue through the next two semesters of design. Phase three will then be initiated upon the completion of the second phase.

3.0 PHYSICAL DESCRIPTION

3.1 AIR REVITALIZATION SUBSYSTEM

Figure 3.1-1 is a diagram of the Air Revitalization (AR) subsystem. The purpose of this subsystem is to regenerate oxygen from CO_2 produced primarily by respiration. The AR subsystem removes carbon dioxide, and trace contaminants from the cabin atmosphere. It in turn breaks down the carbon dioxide into solid carbon and oxygen with some potable water as a by product. The subsystem is composed of four parts, the Carbon Dioxide Removal System, the Carbon Dioxide Reduction System (CRS), the Oxygen Generation Assembly (OGA), and the Trace Contaminant Control System (TCCS). With the exception of the TCCS, each of these subsystems will be described in detail below.

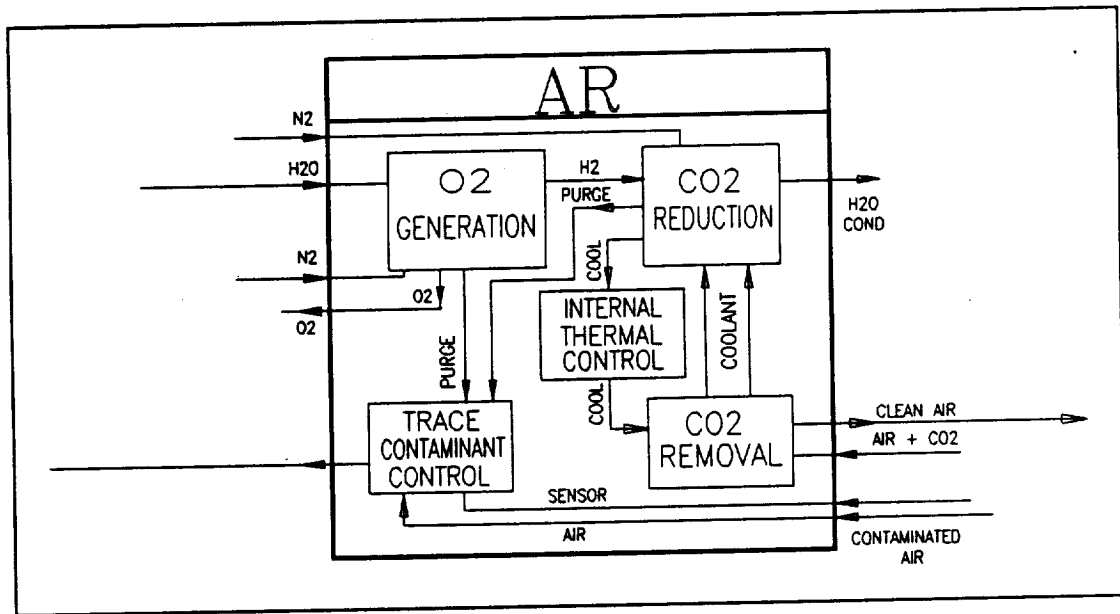


Figure 3.1-1. AR Block Diagram

3.1.1 CARBON DIOXIDE REMOVAL

Metabolic carbon dioxide is removed from the cabin atmosphere by a four bed molecular sieve. The sieve consists of two desiccant beds to remove water vapor from incoming air, two CO_2 adsorption beds, a blower to force the air through the system, a CO_2 pump, a CO_2 accumulator, a pre-cooler, and five multiple-flow selector valves.

Figure 3.1-2 is a diagram of the four-bed molecular sieve. During a typical adsorption cycle, air enters the four-bed molecular sieve from the Temperature and Humidity Control (THC) subsystem (1). After passing through a directional control valve (2), the air enters the desiccant bed (3). Dry air leaves the desiccant bed then passes through another directional control valve (4) before passing through the

blower (5). The air, which has been warmed by the desiccant bed and blower, then passes through a precooling coil (6). After leaving the precooling coil and passing through a third directional control valve (7), the air enters an adsorbing adsorbent bed (8). The CO₂ adsorbent bed, which was heated to release CO₂ earlier, now cools as it adsorbs CO₂. Air leaves the adsorbent bed, passes through a check valve (9), then enters the second desiccant bed (10). This warm dry air evaporates water accumulated in the desiccant bed during its adsorption cycle. This humid, cool air passes through a final directional control valve (11) before returning to the THC subsystem (12).

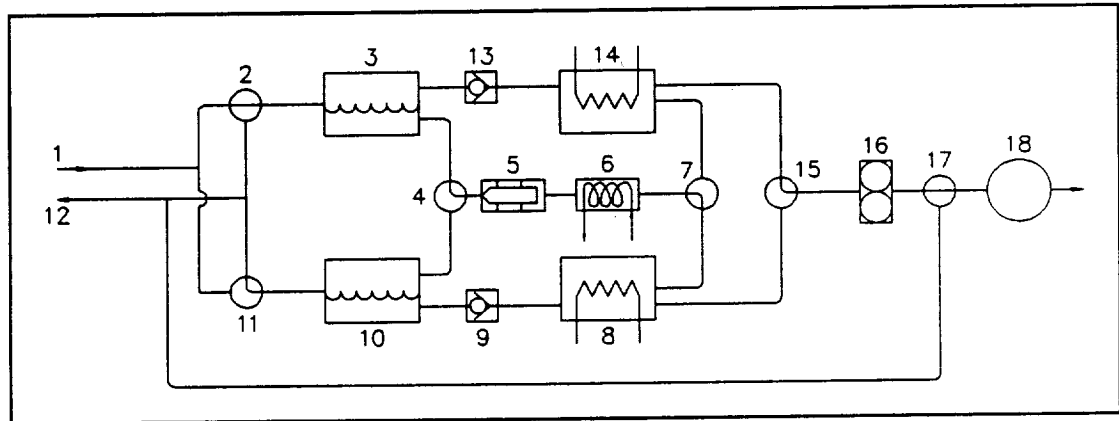


Figure 3.1-2. Four-Bed Molecular Sieve

While one bed is adsorbing CO₂ (8), the other bed (14) is desorbing CO₂. The desorbing begins with an initial pump down of the bed to draw off residual air. A check valve (13) prevents pumping air through the desiccant bed during the desorption cycle. The CO₂ pump (16) pumps air through a valve (15) and back to the THC subsystem through a directional control valve (17). After the initial pump-down, the pump is shut off while heat is steadily applied to the CO₂ adsorption bed by electric heaters. After the bed is sufficiently heated, the pump is restarted. Now the directional valve (17) is set to send CO₂ to the pressurized, fixed-volume accumulator (18).

After the desorption cycle is complete, the valves switch positions and the CO₂-free desorbing bed becomes the adsorbing bed, and the CO₂-filled adsorbing bed becomes the desorbing bed. Likewise, the water filled adsorbing desiccant bed becomes the desorbing bed, and the drier desorbing bed becomes the adsorbing desiccant bed.

DESICCANT BED

The desiccant beds use a highly insulated double wall canister that is filled with layers of adsorbent material. The adsorbent materials used in these beds are Zeolite 13X and Silica gel. Silica gel and Zeolite 13X are placed in separate layers and the

incoming air stream passes over both layers. These two layers are necessary because the silica gel adsorbs water vapor well at high relative humidities but its efficiency decreases for relative humidities of less than 50%. Zeolite 13X, however, is more efficient for relative humidities of 35% or less. The combination of these two layers removes nearly 100% of the water vapor in the incoming stream. As a result of this water removal, the temperature of the air stream increases. These adsorbents readily desorb when the warm exiting air stream passes over them.

BLOWER

The blower is a motor driven centrifugal fan. The motor is designed to operate with 115/220 vac, three-phase, 400 Hz power. De-swirl vanes help convert swirl energy into useful static pressure. The blower is made of corrosion-resistant material with bearings designed to isolate grease from working air.

PRECOOLER

The precooler is a double pass coolant and single pass process-air-flow heat exchanger that is made of stainless steel.

CARBON DIOXIDE REMOVAL BED

The carbon dioxide beds contain heater cores as well as adsorbent material. The adsorbent used to remove CO_2 is Zeolite 5A. It was chosen because of its high carbon dioxide capacity, its good kinetic qualities, and its low water poisoning factor. Because Zeolite 5A can be poisoned by water, it is necessary to use desiccant beds to remove water vapor from the incoming air stream. Since the Zeolite 5A must be heated to release CO_2 , the beds contain heaters.

CARBON DIOXIDE PUMP

The carbon dioxide pump is an electric motor driven rotary vane pump. Except for sealed shaft bearings, the pump is unlubricated to prevent air contamination. The rotor vanes are made of self-lubricating carbon graphite.

CARBON DIOXIDE ACCUMULATOR

The carbon dioxide accumulator is a composite fiber/metal tank. The tank's initial CO_2 pressure of 90 psia will provide 90 minutes of continuous carbon dioxide flow for the CO_2 reduction portion of the AR subsystem. If the accumulator ever becomes too full, the excess CO_2 will be vented.

3.1.2 CARBON DIOXIDE REDUCTION

Figure 3.1-3 is a diagram of the Bosch Carbon Dioxide Reduction System (CRS). This system reduces CO₂ to solid carbon and water. The CRS is designed to operate at one of two constant rates. For a crew of four, 4.36 kg of CO₂ will be processed each day. For a crew of eight, the process rate will be 8.73 kg/day.

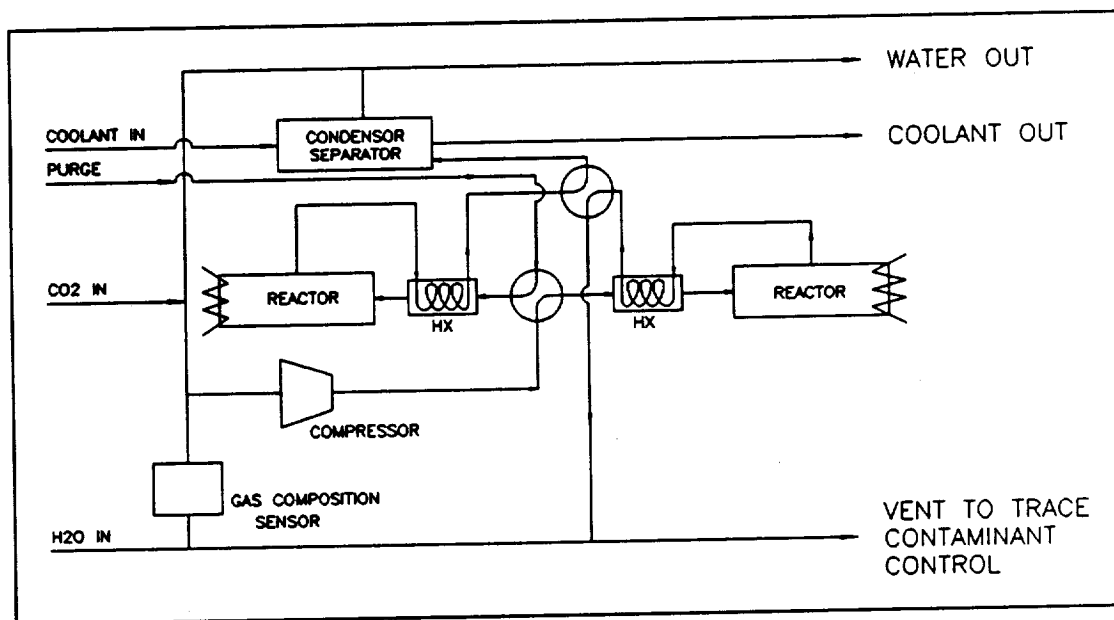
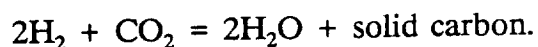


Figure 3.1-3. CO₂ Reduction System

Carbon dioxide from the carbon dioxide removal system and hydrogen from the oxygen generation system are introduced to the CRS in a stoichiometric ratio. This ratio is determined by the following reaction:



Addition of CO₂ and H₂ is regulated according to the composition of the gas circulating in the system. This composition is monitored by a gas sensor in the recirculation loop. The type of sensor to be used is not presently known.

Gases entering the reactor are preheated as they pass through a regenerative heat exchanger. In the reactor, solid carbon is deposited on a catalyst and water vapor is produced. The water vapor and un-reacted gases pass through the hot side of the regenerator prior to entering a condensing heat exchanger. Here the temperature of the gas is reduced below its dew point and the resulting condensate is removed.

The conversion efficiency for this process is approximately 10%. To achieve higher efficiencies for the system it is necessary to recirculate the product gases through the

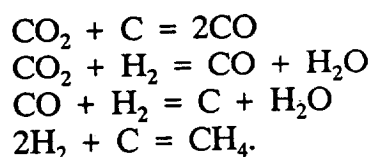
reactor. It is inevitable that some nitrogen will be introduced along with the CO₂ into the system. Resulting pressure accumulation in the recycle loop require periodic venting of this gas. The gas is vented to the trace contaminant control system, however the exact nature of the venting process is not well understood at this time.

The solid carbon collected in the reactors periodically has to be removed. To provide uninterrupted operation, two complete reactors are included in the system. While one reactor is operating, the second reactor is purged with nitrogen. The carbon collection cartridge can then be replaced. Time between change over of reactors is not presently known.

REACTOR

Two types of reactors have been considered for use in the Carbon Dioxide Reduction System. One uses the Sabatier Process, the other the Bosch Process. The Bosch Process has been chosen because it minimizes overboard venting of gases and reduces the launch weight for extended missions. Both process will, however, be discussed.

Bosch - The Bosch Process stoichiometrically adds H₂ to CO₂ and reacts them in the presence of a catalyst. Temperature for this process is between 426°C and 726°C. The reaction that takes place is exothermic producing 2.26MJ/kg CO₂ of heat. A resistance heater is required, however, to start the process. Single pass efficiency for the Bosch Reactor is less than 10%. Complete conversion is obtained by recycling the process gas. Gas in the recycle loop consists of CO₂, H₂, CH₄, water vapor, CO, and inert gas (nitrogen). The inert gas enters in small quantities with the CO₂. Remaining components of the gas are created through the following intermediate reactions:



Major operating parameters that should be considered in the design of the control system for the reactor and their effect on the reaction are listed below in order of importance.

1. Temperature of the reaction. Operating at the higher end of the 426 to 726°C temperature range increases the conversion of the reaction.
2. Recycle flow rate. Increasing the recycle flow rate increases the conversion of the reaction.

3. Catalyst density. Increasing the catalyst density increases the reaction rate and decreases start up time.
4. Gas pressure. Gas pressure has only minor effects on reaction rate. However, increased pressure improves condenser performance and results in a lower content of water vapor in the recycle loop.

Sabatier - The Sabatier process combines hydrogen and carbon dioxide at a temperature of about 620°C. Products of this reaction are water vapor, methane, and other byproducts. A cracking process is then employed to further break the methane down into carbon and hydrogen. In this manner, hydrogen is conserved. The Sabatier's efficiency can reach 99% in converting the H_2 - CO_2 mixture in a single pass. The reaction, taking place in the presence of a catalyst, is self sustaining.

CONDENSING HEAT EXCHANGER

The condensing heat exchanger is used to reduce the temperature of the process gas below its dew point. With the use of "slurper bars" the condensate is collected and removed from the heat exchanger. Slurper bars are tubes that have holes drilled along their length. By passing air (or other gas) through these tubes, a vacuum is created across these holes. It is in this manner that condensate is collected in zero gravity. Slurper bars apparently have advantages over traditional wick type condensate collectors. Little is known about the actual configuration or construction of this component. It is known, however that the cooling fluid is a liquid that is delivered at constant flow rate and temperature.

REGENERATOR

A regenerator is used to preheat gases entering the reactor. By using waste heat from the exhaust gas stream of the reactor, thermal efficiency of the system is increased. The coil of this heat exchanger is of spiral design to minimize inactive areas. Size, material, and other design details of this device are not known at this time.

SEPARATOR

No specific information is known about the construction of this device. Separators used in other systems of the ECLSS use centrifugal force to separate liquid from gas. It is assumed that this device is of similar design.

COMPRESSOR

The compressor is designed to operate at constant speed. Since crew size may vary, two operating speeds are possible, one to accommodate a crew of eight and one for a crew of four. Further information concerning the design of this component has not been located.

3.1.3 OXYGEN GENERATION

The Oxygen Generation Assembly (OGA) module, shown in Figure 3.1-4 uses its four sub-assemblies to turn liquid water into oxygen gas and hydrogen gas. The sub-assemblies are as follows:

- 1) Electrolysis Module
- 2) Water Tank
- 3) Fluid Control Assembly
- 4) Pressure Control Assembly

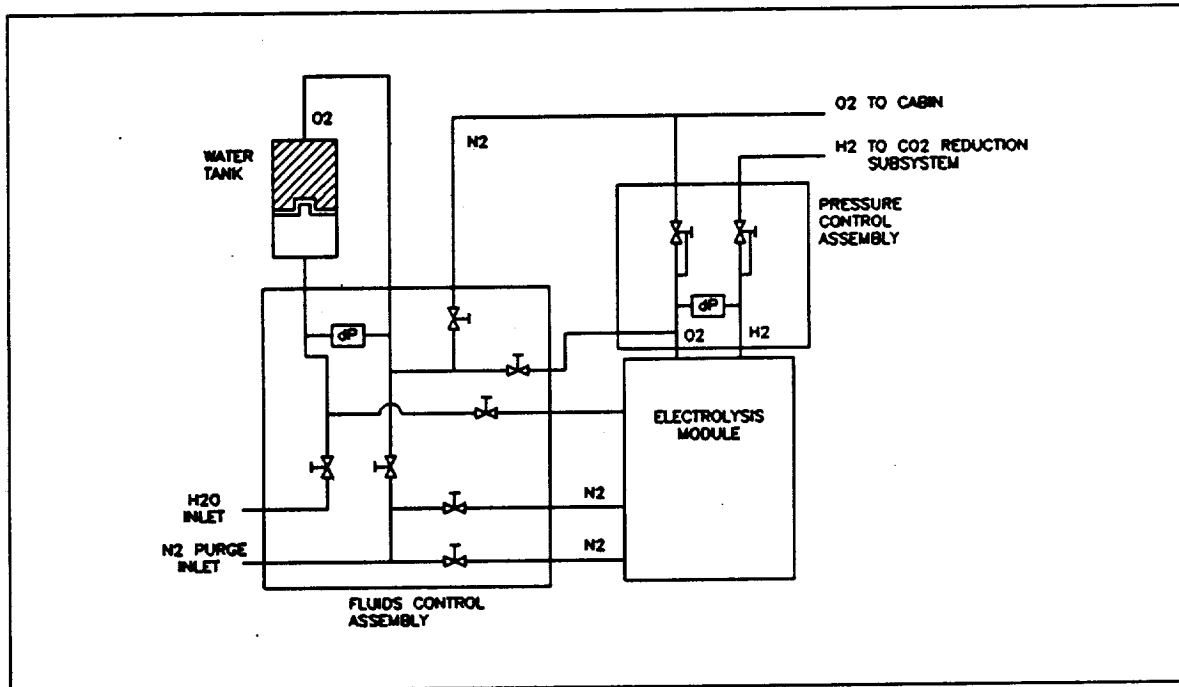


Figure 3.1-4. Oxygen Generation Assembly

The oxygen generated is used for breathing, for airlock re-pressurization, and to compensate for leakage to space. The hydrogen is used by the Carbon Dioxide Reduction module.

ELECTROLYSIS MODULE

The main component in the OGA module is the Electrolysis Module. This module consists of twenty identical cells joined in series electrically, one of which is shown in Figure 3.1-5.

During start-up, the electrolysis chambers are initially filled with nitrogen gas (N_2) in order to purge the existing gases. Once the system is purged, the feed water cavity

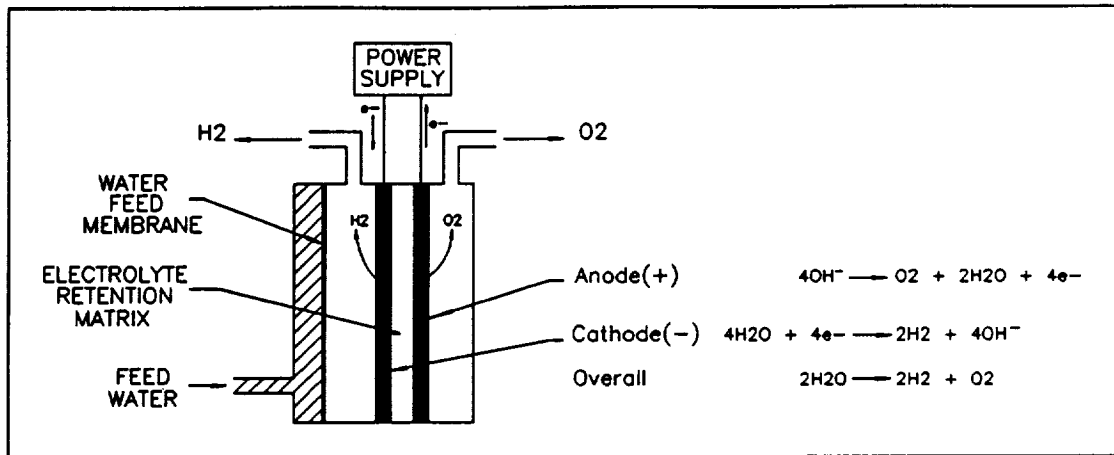


Figure 3.1-5. Electrolysis Cell

is filled with water, a small amount of which diffuses through the water feed semi-permeable membrane in the form of a vapor. As a voltage is applied to the two electrodes, this water vapor chemically reacts with the cathode. This reaction produces hydrogen gas (H_2) and hydroxide (OH). The hydroxide then moves through the potassium hydroxide (KOH) electrolyte to the anode. At this point, there is a chemical reaction that gives off the oxygen gas.

After this small amount of water vapor is electrolyzed, there is a concentration gradient of water vapor between the cathode and the feed water cavity. This gradient causes more water vapor to cross the water feed membrane toward the cathode. Since there is always a voltage difference between the electrodes, (and therefore always a concentration gradient), the module is constantly electrolyzing the water.

The constant generation of hydrogen and oxygen gases requires a constant supply of water. This supply is provided by the water tank, shown in Figure 3.1-4.

WATER TANK

In orbit, there is no gravity to hold the water in a liquid state or to force the water into the electrolysis module. Therefore, the water tank must be pressurized. The pressure is controlled by the pressure of the oxygen produced within the electrolysis module.

FLUID CONTROL ASSEMBLY

The Fluids Control Assembly (FCA) controls the filling and draining rates of the water tank. The FCA is made-up of seven cam-activated two-way valves (that are

integrated into a single valve body), motor-actuators, pressure transducers, check valves and filters.

PRESSURE CONTROL ASSEMBLY

The water Pressure Control Assembly (PCA) maintains the absolute and differential pressures in the electrolysis module and controls the pressurization and the depressurization of the subsystem during start-ups and shut-downs. The PCA consists of two motor-driven pressure regulators (one for the O₂ and one for the H₂). These regulators work together with one differential pressure sensor and one absolute pressure sensor to control the pressure of the oxygen and hydrogen gases leaving the OGA module.

3.2 TEMPERATURE AND HUMIDITY CONTROL SUBSYSTEM

The principal function of the Temperature and Humidity Control (THC) subsystem is to maintain a comfortable environment for the astronauts in Space Station Freedom (SSF). The subsystem has three functions: 1) to control the temperature and humidity of the cabin air; 2) to cool the equipment racks; and 3) to provide refrigeration for food storage and laboratory experiments (3.2-1). Figure 3.2-1 is a general schematic of the THC subsystem.

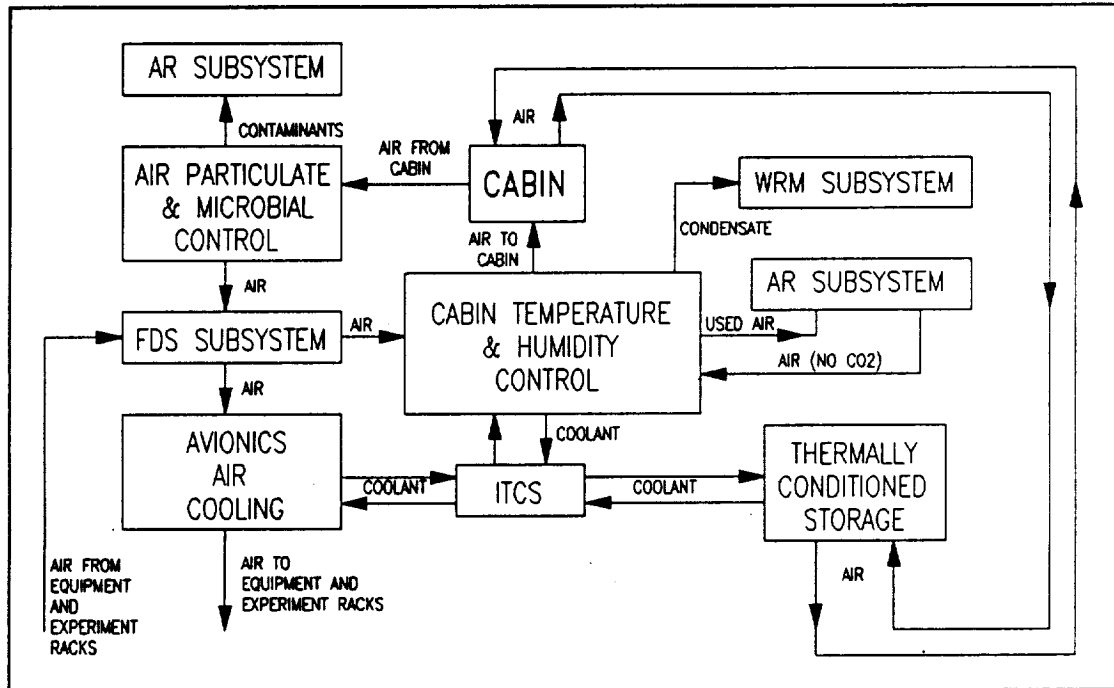


Figure 3.2-1. THC Block Diagram(3.2-1)

Three other subsystems work in conjunction with the THC subsystem (Figure 3.2-2). The Atmosphere Revitalization (AR) subsystem supplies breathable air to be conditioned and distributed by the THC subsystem. Air containing CO_2 is then returned to the AR subsystem for reprocessing. Contaminates removed from the air by the THC subsystem are also sent to the AR subsystem (see Atmosphere Revitalization section of report).

Condensate collected during dehumidification processes is sent to the Water Recovery and Management (WRM) subsystem to be processed and reused as potable water (see Water Recovery and Management section of report).

Sensors detecting temperature changes and ionization of gases are located throughout the duct work, racks and cabin area of the space station. These sensors are electronically connected to the Fire Detection and Suppression (FDS) subsystem.

If data collected by these sensors indicate that a fire exists, the FDS subsystem activates the fire depression mode of operation. Air distributed by the THC subsystem is continuously circulated past FDS sensors (see Fire Detection and Suppression section of report).

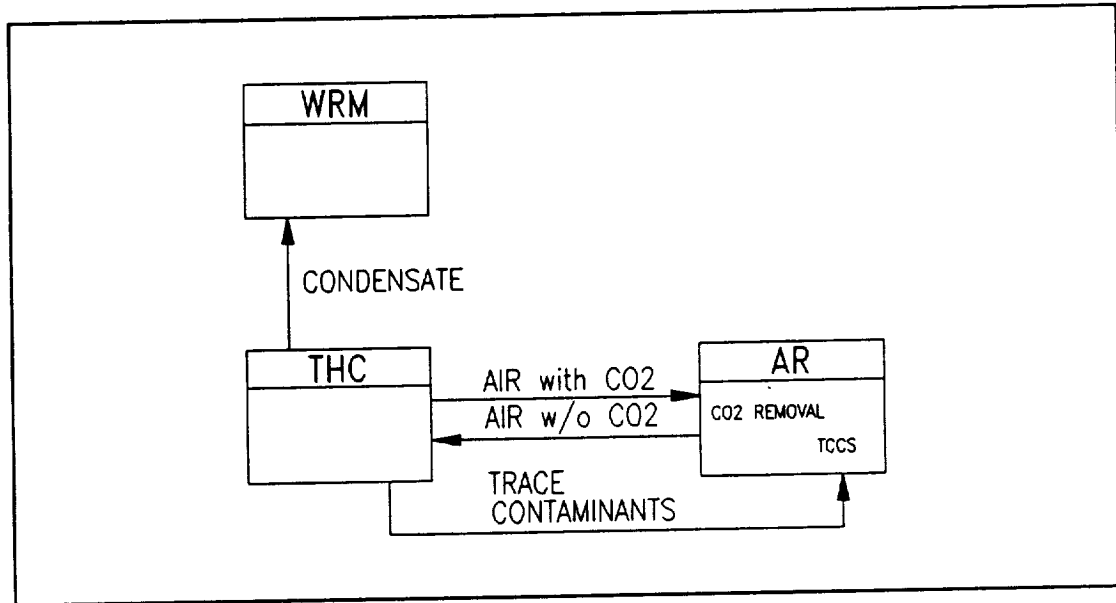


Figure 3.2-2. THC with AR, WRM and FDS

The Internal Thermal Control System (ITCS) removes heat acquired during the air cooling and dehumidification processes of the THC subsystem. Dual-fluid (water-to-water) heat exchangers cool the air which is distributed to the cabin, the racks and the thermally conditioned storage areas. Water is the most appropriate heat-transport fluid since it is nontoxic and nonflammable, chemically and thermally stable for long periods of time, has a high thermal conductivity and heat capacity and has a low dynamic viscosity (3.2-2). The ITCS is not considered an ECLSS subsystem since it does not have a direct effect on the space station environment. The primary purpose of the ITCS is to remove heat acquired by the six ECLSS subsystems.

TEMPERATURE AND HUMIDITY CONTROL SUBSYSTEM COMPONENTS

Four components comprise the THC subsystem. These components are the cabin temperature and humidity ventilation control, air particulate and microbial control, avionics air cooling and thermally conditioned storage.

Temperature and Humidity Ventilation Control - Figure 3.2-3 is a schematic of the cabin temperature and humidity ventilation control. The ventilation system consists of fans to control the air flow rate and duct work to direct the air flow. A condensing heat exchanger controls the cabin air temperature and humidity.

Temperature and pressure sensors are placed throughout the system in order to check operating conditions.

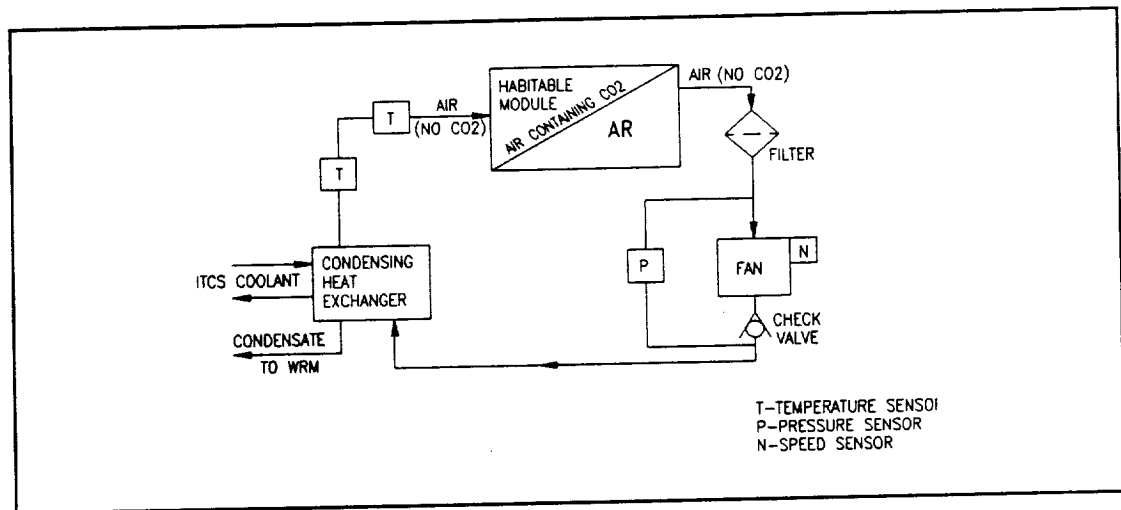


Figure 3.2-3. Temperature and Humidity Ventilation Control (3.2-1)

The condensing heat exchanger, which controls the cabin air temperature and humidity, is a dual-fluid (water-to-water), four pass, counterflow heat exchanger (Figure 3.2-4). Dual-fluid flow refers to two fluid flow loops integrated into one heat exchanger assembly, each of which are four pass. Air flow is perpendicular to the fluid flow direction (counterflow). The heat exchanger is constructed of stainless-steel to decrease the possibility of corrosion and wear. Short, densely packed fins are used to increase the fin surface area. The added surface area helps to increase the heat exchanger efficiency. Improved efficiency permits the use of a smaller core which in turn decreases the size and weight of the heat exchanger (3.2-3).

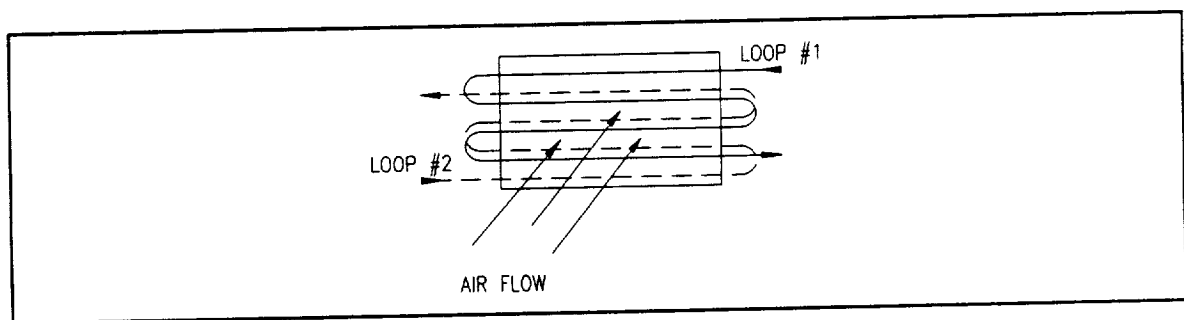


Figure 3.2-4. Dual-Fluid, Counterflow Heat Exchanger

Condensate is a by-product from cooling and dehumidifying the air by passing it through a heat exchanger. On earth, gravity causes this condensate to "fall" to a collection area. In space, the condensate "floats" and does not collect in one area.

The method for collecting this condensate in space used on SSF is a device called a "slurper" (Figure 3.2-5).

The slurper is a separator/pump assembly that draws water out of the air stream. Air/condensate mixtures exiting the heat exchanger are drawn over flat plates drilled with small, evenly spaced holes. The plates are covered by a hydrophilic coating which acts as a wettable surface to help attract the water to the plates. Once the water is drawn to the plates, it is pulled through the holes by a suction between the plates created from negative pump pressure. The water is then circulated to storage tanks in the WRM subsystem (3.2-4).

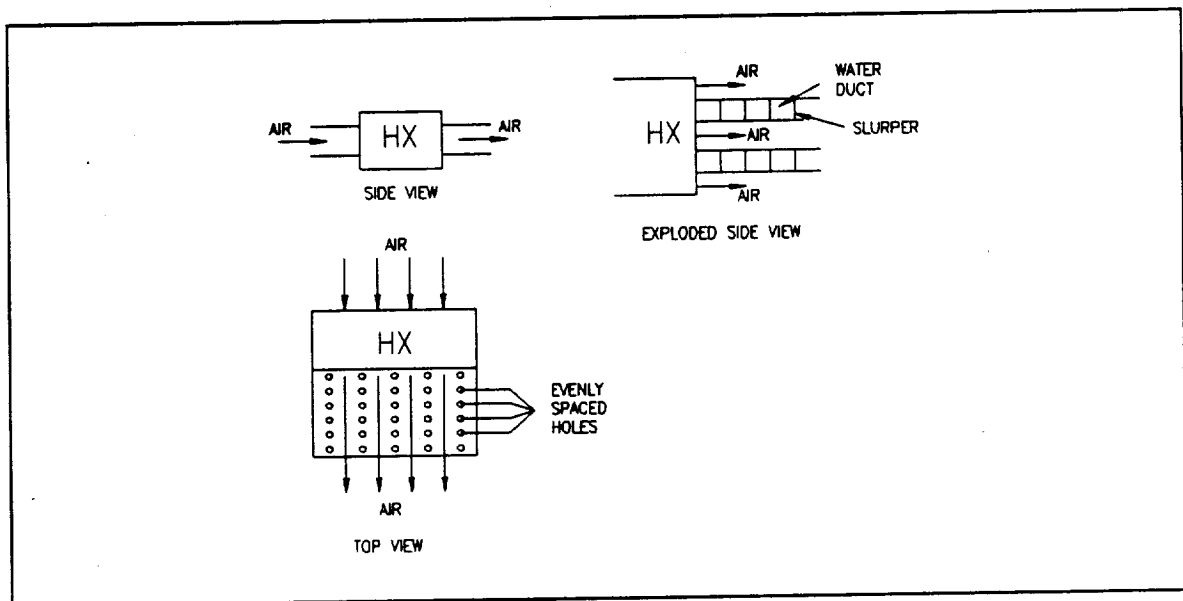


Figure 3.2-5. "Slurper" (3.2-4)

Air Particulate and Microbial Control - The air processed in the AR subsystem must pass through filters before being distributed by the THC subsystem (Figure 3.2-3). These filters remove unwanted airborne particulates and microbial contaminants (bacteria) from the air.

Avionics Air Cooling - Avionics air cooling provides cooling to the equipment racks. Air circulates continuously past power consuming equipment and combustible material storage racks. Heat exchangers cool the air and fans circulate it throughout the equipment and storage rack areas (Figure 3.2-6). Cabin air which has already been circulated through the cabin is cooled and then circulated through the avionics before it is returned to the AR subsystem for reprocessing.

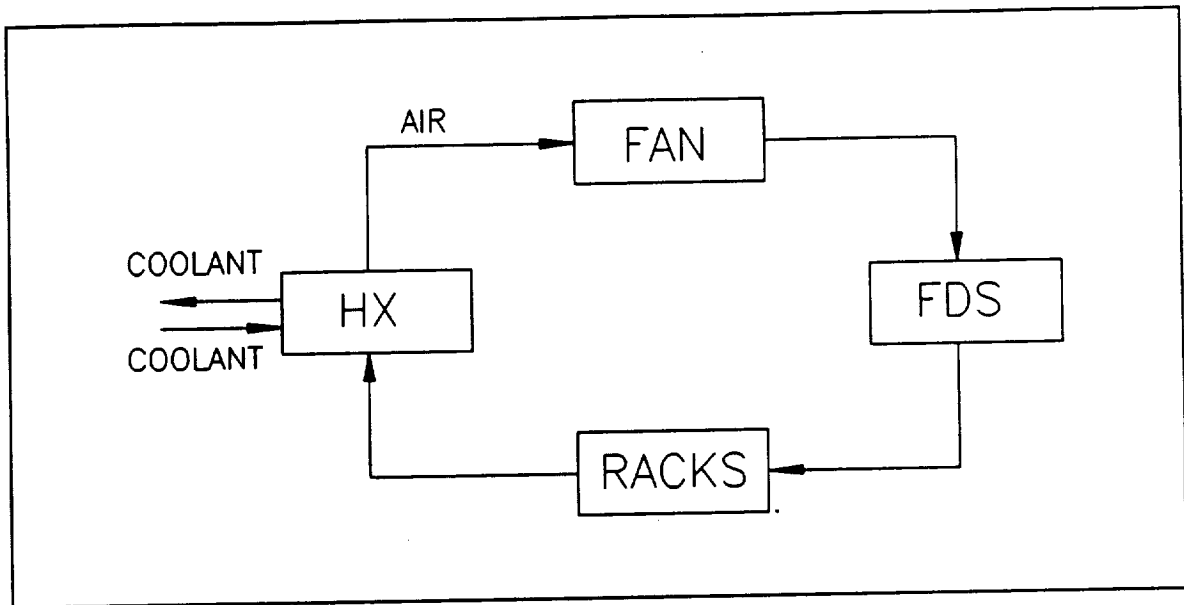


Figure 3.2-6. Avionics Air Cooling

Thermally Conditioned Storage - Figure 3.2-7 illustrates the freon, air and water loops of the thermally conditioned storage system. The refrigeration loop consists of an expansion valve, evaporator, compressor and condenser through which the freon travels. The freon removes heat from the air passing through the evaporator. The air is circulated by fans through ducts into and out of the various storage compartments.

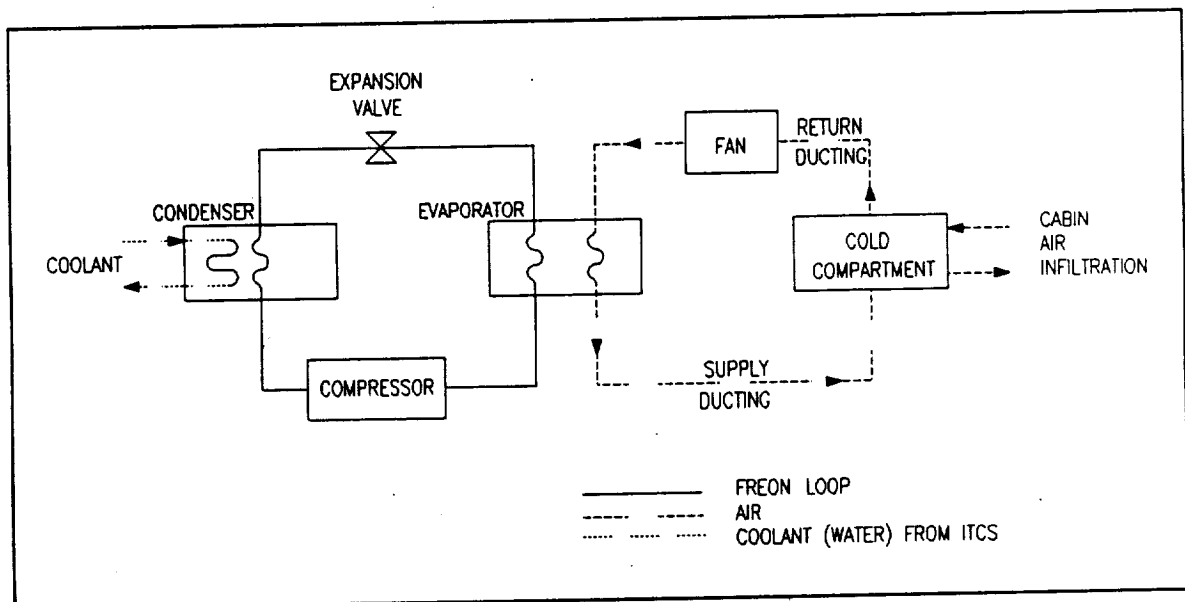


Figure 3.2-7. Thermally Conditioned Storage(3.2-5)

CONCEPTUAL DESIGN

Air Particulate and Microbial Control: Filter specifications have not been identified by the 1989/90 student design team. Filters used for industrial applications such as for clean room facilities and medical research facilities are probably similar to those used on SSF. Contacting an industrial filter manufacturer and/or a product representative or design firm who specializes in this area would probably be helpful in deciding appropriate filter specifications.

Avionics Air Cooling: The air which has been circulated past the avionics probably returns to the cabin temperature and humidity control units before it is recirculated into the habitable portions of the cabin. Most likely, a negative pressure exists within the avionics racks in order to draw the air from the cabin to the racks, for fire safety reasons. Direct contact with NASA researchers could verify these assumptions.

Thermally Conditioned Storage: Air is probably circulated into and out of these units just as air circulates through a household refrigerator. The result is that air exchanges with the cabin mostly occur when the unit doors are open as well as limited air exchanges from infiltrations around the unit door seals. NASA researchers would be helpful in answering questions about the system.

For the most part, temperature and humidity control is not a new concept to space technology. Conditioning an environment in space is much like conditioning an environment on earth with the exception of a few problems arising from zero gravity. As a result, there are not many current reports written specifically on the THC subsystem.

3.3 WATER RECOVERY AND MANAGEMENT SUBSYSTEM

The Water Recovery and Management subsystem (WRM) is responsible for supplying the crew of the Space Station Freedom (SSF) with potable and hygiene water. Potable water is utilized for crew consumption, and hygiene water is used for hygiene purposes.

In the ECLSS, the sources of potable water are the Temperature and Humidity Control subsystem (THC), and the Atmosphere Revitalization subsystem (AR). Condensate is retrieved from these two subsystems and stored in the WRM subsystem. The condensate is then processed into potable water and either stored or sent to the cabin for crew consumption (see Figure 3.3-1).

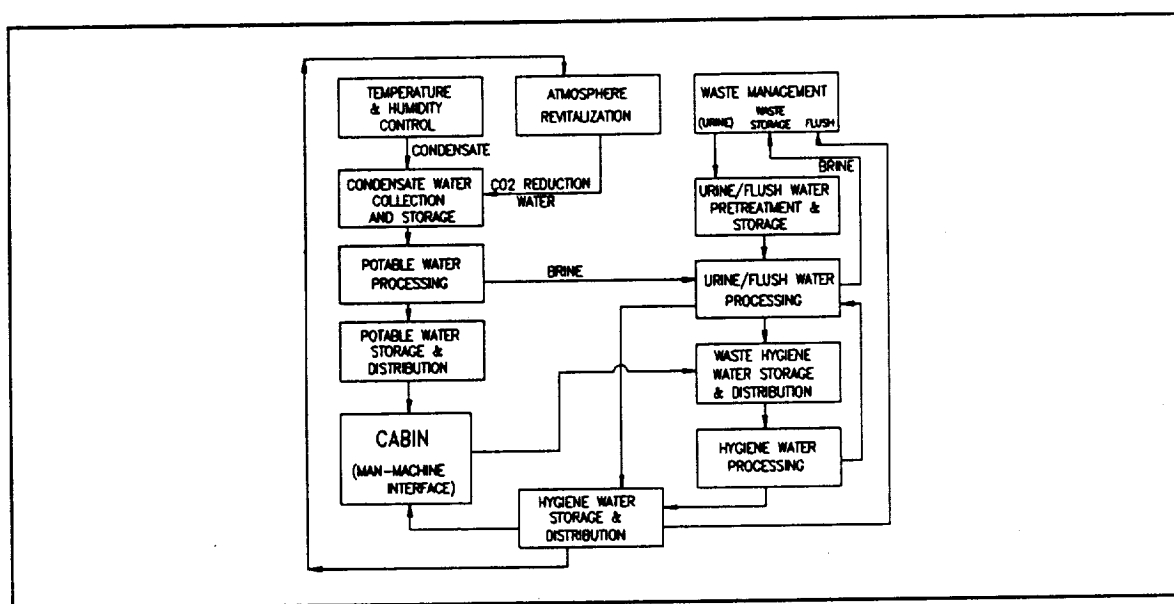


Figure 3.3-1. WRM Block Diagram

Hygiene water is continuously recycled within the ECLSS. All water can be processed into hygiene water, including urine. There are three inputs to the hygiene water processing water operation in the WRM subsystem; Waste Management subsystem (WM), the cabin, and the potable water-processing module (see Figure 3.3-1). The latter is within the WRM subsystem and will be discussed later in the module descriptions. For the WM subsystem, urine is transported from the WM subsystem to the WRM subsystem (urine combined with flush water). It is then treated and processed into hygiene water. The waste hygiene water which comes from the cabin, is processed in the WRM subsystem. This water does not need to be processed and treated to the extent of the urine/flush water.

There are three outputs of the WRM subsystem. The first involves the use of hygiene water which is processed and sent to the AR subsystem. This water is used

in the electrolysis process to generate oxygen. The second output involves sending processed hygiene water to the cabin to be used by the crew. The third output is the flush water sent to the WM subsystem (see Figure 3.3-1).

The inputs and outputs of the WRM subsystem modules discussed above are monitored with sensors and control valves. If the flow rates are not monitored, there is a risk of flooding one module while draining another. The flow rates must also be monitored in order for the WRM and entire ECLSS to work efficiently. The following modules, discussed below, are shown in Figure 3.3-1.

CONDENSATE WATER COLLECTION AND STORAGE

The condensate water collection and storage module is the first step in the potable water-processing procedure. Condensate from the THC and water from the AR subsystems is collected and stored in this module. Sensors and control valves monitor how much condensate water and CO₂ reduction water are sent to this module. Sensors are also necessary to monitor the amount of water in the module at a given time. Finally, a sensor and control valve are necessary to monitor the amount of water which leaves this module and goes to the Potable Water Processing module.

POTABLE WATER PROCESSING

The condensate water is processed into potable water in this module. During the processing operation, brine is produced. The brine is sent to the Urine/Flush Water Processing module where it is processed into hygiene water. It is necessary to monitor the amount of brine sent to the Urine/Flush Water Processing module and the amount of potable water sent to the Potable Water Storage and Distribution module. The amount of water in the module itself must also be monitored.

POTABLE WATER STORAGE AND DISTRIBUTION

The function of the potable water storage and distribution module is to store and distribute potable water. The amount of water in the module and the amount of potable water being sent to the cabin must be monitored.

URINE/FLUSH WATER PRETREATMENT AND STORAGE

The urine/flush water pretreatment and storage module is the first module in the hygiene water-processing procedure. This module collects and stores urine/flush water from the WM subsystem. In this module, the urine/flush water coming from the WM subsystem must be monitored and controlled, as well as the treated urine/flush water leaving this module and going to the Urine/Flush Water Processing module. Also, the amount of urine/flush water in the module at a given time must be monitored.

URINE/FLUSH WATER PROCESSING

In the urine/flush water processing module, urine/flush water, brine, and waste hygiene water are all processed into hygiene water. Many sensors and control valves are necessary in this module because of the large amount of inputs and outputs. The inputs that must be controlled are the brine, which comes from the Potable Water Processing module, and the hygiene water (used to treat the urine/flush water), which comes from the Hygiene Water Processing module.

Three hygiene water outputs must be controlled. One output goes to the Hygiene Water Storage and Distribution module, the second output goes to the WM subsystem (to be used to treat waste), and the third output is sent to the Waste Hygiene Water Storage and Distribution module (This water is being used to treat the waste hygiene water from the cabin).

WASTE HYGIENE WATER STORAGE AND DISTRIBUTION

The waste hygiene water from the cabin is sent to the waste hygiene water storage and distribution and is stored with processed urine/flush water. In this module, the waste hygiene water coming from the cabin must be monitored, as well as the waste hygiene water going to the Hygiene Water Processing module.

HYGIENE WATER PROCESSING

The waste hygiene water is processed back into hygiene water. Some of this water is then sent back to the Urine/Flush Water Processing module to aid in that module's processing operations. The amount of water sent back to the Urine/Flush Water Processing module must be monitored. The rest of the water is sent to the Hygiene Water and Storage Distribution module. This water must be monitored also.

HYGIENE WATER STORAGE AND DISTRIBUTION

In the hygiene water storage and distribution module, the processed hygiene water is stored, and then distributed to the cabin, the AR subsystem and the WM subsystem. The inputs to this module are already monitored by the modules from which they come. The outputs, however, must be monitored. There are three hygiene water outputs from this module. The first output goes to the AR subsystem. The hygiene water is used in the AR subsystem to create oxygen using electrolysis. The second output goes to the cabin. The hygiene water is used in the cabin for full-body shower, hand-washing, clothes-washing, and dish-washing. The third output is to the WM subsystem. In this subsystem, hygiene water is used as flush water.

3.4 WASTE MANAGEMENT

INTRODUCTION

The Waste Management (WM) subsystem is a part of a more complex system called the "Integrated Waste and Water Management System". The system uses a distillation process for purifying waste water, a catalytic oxidation process for microbial digestion, and incineration for waste disposal. The primary responsibility of the waste management subsystem is to provide processing and storage of fecal wastes.

WASTE INPUTS: Urine, feces, waste water, non-metallic trash, and food.

WM SUBSYSTEMS: Feces, trash, and urine collection; water reclamation; storage, heating and dispensing of water, disposal of the feces and urine residues; and all other waste material, including trash, by incineration.

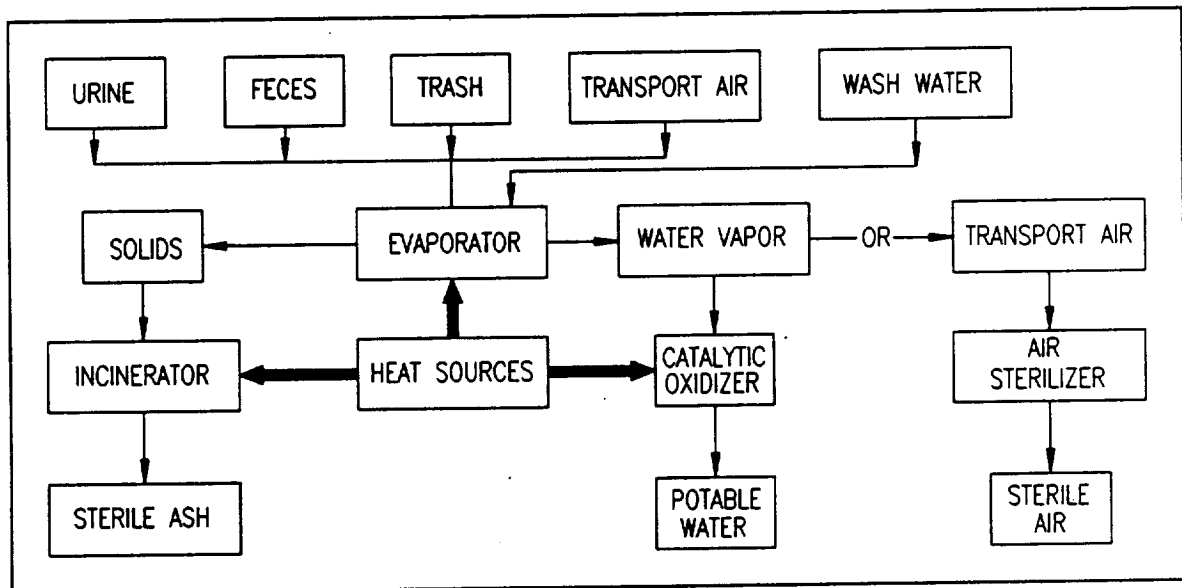


Figure 3.4-1. WM Block Diagram (3.4-1)

DESCRIPTION

All wastes are collected in the evaporator where the waste content is distilled at low temperature of 49°C, and the remaining solids are centrifugally removed from the evaporator. The distilled water vapor contains a small amount of impurities which are centrifugally oxidized at 649°C. Following condensation of the water vapor, the non-condensable gases separate from the water and are vented from the system to the water recovery system. The resulting pure and sterile water is ready for potable water use.

The solid wastes are taken to another storage area where they are sterilized, dried, and thermally decomposed. This area contains all the solid waste generated by the operation of the Space Station Freedom (SSF). After the storage container reaches maximum capacity, the waste is sent to the incinerator. In the incinerator, oxygen is added and the solids are incinerated and reduced to ash. The ash, which is 1% of the solid waste input, and the resulting gases, are vented to space vacuum or back to the cabin environment through the Atmosphere Revitalization (AR) subsystem.

THE EVAPORATOR

The evaporator receives all the wastes and provides solid/liquid separation by centrifugal action. Initial purification is by distilling the wastes at a reduced temperature (49°C), and a pressure of 80mm Hg. The transport airflow used to convey wastes into the collection devices and then into the evaporator is created by a suction blower. The blower then forces air through the air sterilizer before it is returned to the cabin or to the AR subsystem.

THE COLLECTION SUBSYSTEM

The collection subsystem consists of the commode, urinal, trash shredder and associated equipment.

- * The commode utilizes a water flush after defecation, tissue wipes are also accommodated.
- * The feces are conveyed into the blender via airflow from zero "G" operation, here the feces are mixed with the flush transport air to the evaporator.
- * The urinal also uses air flow to convey the urine into a liquid/gas separator.
- * Trash is manually placed into the shredder as desired for late processing when the commode is used.
- * The plastic and paper trash and garbage are shredded and mixed with water then pumped into the evaporator.
- * Wash water from the galley, shower and clothes washer are also periodically added to the evaporator as required.

THE INCINERATOR

The incinerator consists of a motor drive shuttle in a sealed cylinder. The solids are pumped by the auger into the shuttle positioned at the cool end of the cylinder, after being filled the shuttle is moved into a higher temperature zone where the solids are initially dried, and thermally decomposed. Finally, oxygen is added and the remaining solids are incinerated, and the gases vented. After incineration the shuttle is returned to the cool end and the remaining ashes are blown into a filter for collection.

QUESTIONS TO BE ANSWERED

- 1) About the evaporator: Of what materials is made? Does it control for the amount of material that is put in it? Are there sensors or devices that will signal when it is filled? Does it function in a steady setting (the same temperature all the time?). How often does it run?
- 2) About the incinerator: Of what materials is made of? How does it control for the amount of material that is put in it? Does it have a sensor device? If so, where is it located? What is its capacity? How often does it run?
- 3) About the heat sources: What are they? Where are they specifically located? How much heat is released into the system? and how often? How is the amount of heat controlled? By what mechanisms? Is there any sensor that controls it?

3.5 FIRE DETECTION AND SUPPRESSION

The function of the Fire Detection and Suppression (FDS) subsystem is to ensure the safety of station inhabitants by providing for the detection, assessment, and suppression of on-board fires. This ECLSS subsystem will utilize a network of sensors and a variety of suppression methods to provide the most effective and appropriate response to a fire threat. "Fires are first located, their magnitude determined, and then they are isolated."(3.5-1)

The FDS subsystem is comprised of two primary modules: Detection and Suppression. The schematic diagram in Figure 3.5-1 illustrates the interaction between the FDS subsystem, other ECLSS subsystems, and certain compartments within the space station.

Air from the cabin, experiment racks, and avionics air cooling is constantly circulated through the detection elements. If a fire is detected, the suppression module can release a suppressant into these compartments(3.5-1). The Temperature and Humidity Control (THC) subsystem plays an active role in the detection process by monitoring various temperature levels throughout the station. A more detailed explanation of the FDS subsystem follows.

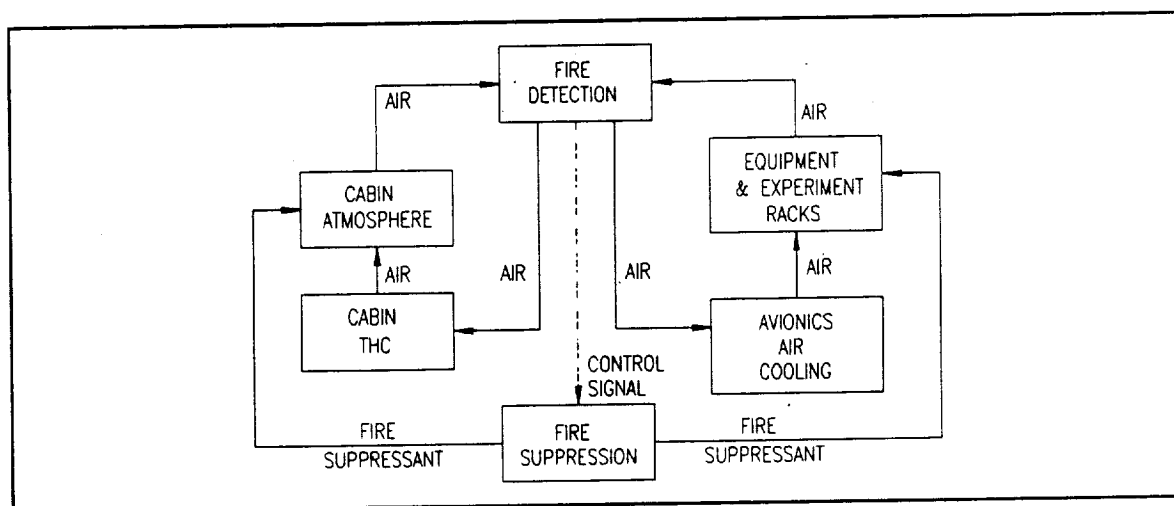


Figure 3.5-1. FDS Block Diagram (3.5-2)

Note: Air flow shall cease upon fire detection and release of fire suppressant.

DETECTION

The detection of fires will be performed by a network of sensors. "Sensors are being tested that can detect fires in the four stages of combustion: incipient, smoldering,

flame, and heat."(3.5-1) Sensors that are being considered include ionization detectors, infrared/ultraviolet sensors, and thermal sensors (3.5-1). An active ionization detector has been produced to detect sub-micron pyrolytic matter, however, the actual sensors to be used aboard SSF have not yet been determined(3.5-1).

A network of sensors implies that each type of sensor will generate independent input signals to a common data base. The various sensors will serve as the primary input devices to the detection module. The evaluation of this input data will be performed by a detection software system to be developed later in the design.

The detection network will allow the FDS subsystem to determine exactly where the fire is located as well as determine the magnitude of the fire. By interlocking the sensor network, the sensors have a cross-check mechanism. For example, if a fire breaks out in the avionics air cooling racks, then ionization sensors should sense the presence of smoke particles, thermal sensors in the rack should detect higher local temperatures, and infrared sensors should identify an infrared signature characteristic of a fire. By spacing the sensors throughout the craft, this cross-checking of sensors allows the FDS subsystem to identify the exact location of the fire. Similarly, this cross-checking helps minimize erroneous fire alarms.

A human interface with the detection system is yet to be developed but should include manual fire alarm switches, a manual override of the system, and an audio (sirens or bells) and visual (flashing lights) warning system to alert the inhabitants of a fire danger. The detection network should also download all relevant data to a computer terminal so that the astronauts can see at a glance where the fire is, how large the fire is, and the actions that the suppression system will undertake to combat the fire.

One question that remains to be answered is "how much control should the humans have over the FDS subsystem?" On one hand, human interfacing is not desirable because people are slow making decisions relative to computers. In the delicate balanced environment of the station, if proper action is not taken immediately, the consequences could be disastrous. On the other hand, computer hardware and software has been known to malfunction thus humans are not yet willing to give complete control of a situation to machines. The proper hierarchy balance for the FDS subsystem should be developed in cooperation with the automated control system in future design work.

The actual spacing of the various types of sensors has not been determined yet it will be largely dependent on the effective operating range of the sensors and the total air space in a particular module or compartment. The smoke detectors are ionization detectors and each of the 9 detectors have a small fan that forces air through the device. It is anticipated that this same procedure will form the basis for the SSF smoke detection system.

Due to the tremendous amount of data generated and the complexity of identifying a fire and its location, actual development of the FDS subsystem must include the use of "expert" software systems. These systems will process the data and allow "expert" decisions to be drawn from a vast data base almost instantaneously. Expert Systems are an offshoot of Artificial Intelligence and should be examined while the detection system is being developed.

System designers will also have to make sure that the FDS detection system design is compatible and easily integrated with the systems developed for the European and Japanese Space Agency modules.

SUPPRESSION

The suppression module consists of the tanks and distribution system (nozzles and pipes) necessary to supply the fire suppressant to equipment racks, standoffs, and portable extinguishers and the relays, switches and solenoids necessary to control external devices. This module will be responsible for implementing the most appropriate response to a fire threat as determined by an "expert" suppression software program or human interfacing. Once a fire has been detected, suppression "expert" software will choose the most effective actions to suppress the given fire. The software will then control the operation of the various hardware components needed to enact the response. Five primary methods of fire suppression will be utilized (3.5-3):

- 1) Introduction of CO₂ or Halon suppressant
- 2) Addition of N₂ to environment
- 3) Shut down of electrical and air flow systems
- 4) Manual fire suppression
- 5) Evacuation of module air

As stated before, fires are first located, assessed by the software or humans, and then they are isolated. "Isolation is first performed at the rack level by cutting off airflow through the rack, releasing suppressant into the rack, and removing power from the rack. Second, if needed, the intermodule airflow is shut off, hatches are closed, and the module atmosphere is vented to space."(3.5-1) At this point it is not known how each rack will be isolated. However, by designing a particular rack area with its own air intake and exhaust, it would be possible to shut the airflow to that particular area off by closing the intake and exhaust shutters.

As discussed before, the safety of the crew and the craft depend largely upon how fast an appropriate response is enacted. It is essential that the components of this system be both reliable and able to respond fast (micro-seconds) to electrical signals.

Halon gas or CO₂ will be used as the suppressant. Halon 1301 is a better suppressant for flammable liquid and electrical fires, but it has been criticized for being mildly toxic. CO₂, however, provides easier cleanup in a closed environment(3.5-1). In the event of a fire suppression, cleanup could be performed by vacuuming the suppressant off of station hardware and components. The Air Revitalization subsystem would then need to clean the contaminants (smoke and suppressant) out of the cabin air.

The outlined Fire Detection and Suppression system is based on the assumption that electrical power will be available to the system components during its operation. Manual fire detection and suppression could be performed by the station inhabitants but it is recommended that great care be taken to insure that the craft and inhabitants will not be vulnerable to fire in the event of electrical power failure.

UNIQUE PROBLEMS IN MICROGRAVITY ENVIRONMENT

The microgravity environment creates several unique problems for the FDS system designer. In zero gravity there is no natural convection as on earth. Therefore, ionization sensors (smoke detectors) are only useful when there is a forced air flow through these devices. As shown earlier, each ionization detector has a small fan that forces air into the unit. Secondly, a flame in space does not burn upward as on earth; it takes on a spherical shape and burns outward in all directions(3.5-3). This makes the spread of the fire more unpredictable than on earth. Flames burning on material are also able to "float" about the cabin igniting objects in their path. Another concern for system designers is the fact that dust particles not removed by the Air Revitalization system will not settle onto surfaces. Instead, they will tend to stay airborne, thus increasing the risk of a rapid spreading dust fire(3.5-3).

3.6 ATMOSPHERIC CONTROL AND SUPPLY SUBSYSTEM

The Atmospheric Control and Supply (ACS) subsystem controls the pressurization of all gas compositions for the Space Station Freedom (SSF) cabin. This subsystem maintains a cabin pressure of 14.7 psi as well as regulates the amount and partial pressure of oxygen and nitrogen in the cabin atmosphere. Atmospheric leakage of the modules, experiment ventilation, airlock pressure losses and pressure venting are all functions of the ACS subsystem. Oxygen and nitrogen storage and distribution equipment are also part of the subsystem (Figure 3.6-1).

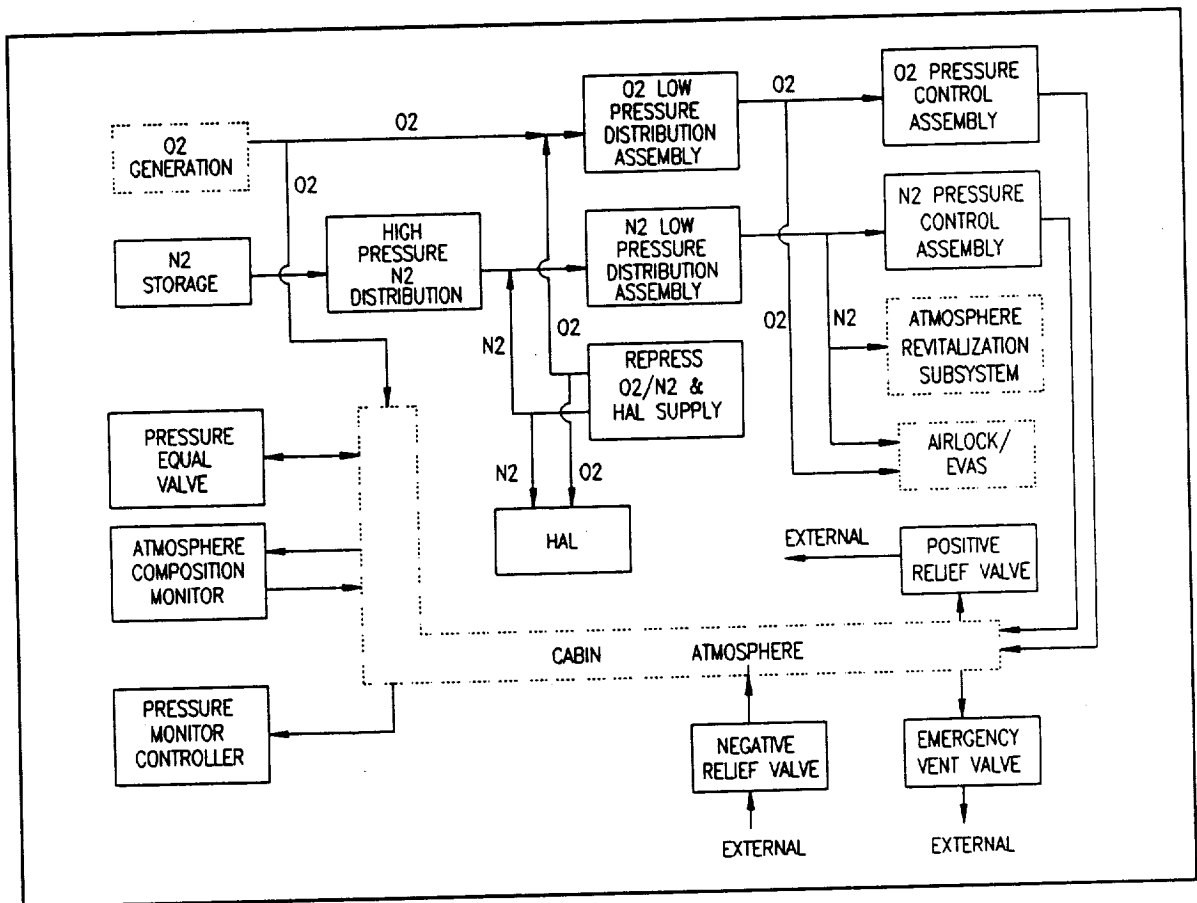


Figure 3.6-1. ACS Block Diagram (3.6-1)

The ACS subsystem is categorized into five functions: oxygen/nitrogen pressure control; vent and relief; oxygen/nitrogen storage; oxygen/nitrogen distribution; and atmosphere composition monitoring. Definitions of these functions are given below.

Oxygen/Nitrogen Pressure Control - The total and the O_2/N_2 partial pressures are regulated and controlled by the ACS subsystem. The subsystem also repressurizes any part of the SSF if an unexpected atmospheric losses occur.

Vent and Relief - The ACS subsystem is capable of preventing over or under pressurization of the modules and of equalizing the pressure between the modules.

Oxygen/Nitrogen Storage - Oxygen and nitrogen are stored in order to re-pressurize the cabin if necessary and to provide nitrogen to the cabin atmosphere.

Oxygen/Nitrogen Distribution - A complete distribution system containing internal/external lines, valves and quick disconnects provide oxygen and nitrogen to the ACS subsystem components.

Atmosphere Composition Monitoring - The ACS subsystem has trace contaminant monitoring capabilities and sensors to measure the oxygen partial pressure. The subsystem is also able to balance the gas composition of the cabin atmosphere.

4.0 CONCEPTUAL CONTROLS

4.0 CONCEPTUAL CONTROLS

INTRODUCTION

This chapter details the progress made by the Conceptual Controls group toward the design of a control system for the Air Revitalization system of the ECLSS. The Air Revitalization system was divided into three sections with different individuals being responsible for the design of a local control system for each section. The sections are 1) CO₂ Reduction, 2) CO₂ Removal, and 3) O₂ Generation.

When formulating a control scheme, astronaut safety was paramount, however factors such as control system complexity, reliability, cost, system efficiency, and power consumption were also taken into account.

Each section of this chapter contains a description of the current control scheme, the proposed control scheme, and a sensor layout detail. In addition, a comparison is made between the current and proposed control systems.

4.1 CO₂ REMOVAL CONTROL

CURRENT CO₂ REMOVAL CONTROL SCHEME

The control scheme which is presently used is a two-cycle process based solely on time. The removal system runs continuously with the role of each pair of desiccant and adsorbent beds performing the opposite function of the other pair in each half-cycle. Each half cycle is 55 minutes long. All selector valves and major system components are controlled using electrical signals and specific time increments. It is not known if there are any sensors in place to allow for failure detection. Figure 4.1-1 shows the state of each bed in the system versus time.

CO₂ Desorbing Phase

During this phase three primary operations occur. These individual operations are sequenced in time. The first operation is the residual air pump down. The desorbing bed is pumped down using the CO₂ pump. Residual air is removed and routed to the cabin via the THC subsystem. Next the CO₂ pump is turned off and the heater in the adsorbent bed is activated. Finally the CO₂ pump and heater are activated for the remainder of the half-cycle and the CO₂ concentrate is channeled into the fixed volume CO₂ accumulator.

PROPOSED CO₂ REMOVAL CONTROL

This control system will be based on the current concentration of CO₂ in the cabin. The control will be achieved by using the signals from several CO₂ gas detectors placed throughout in the cabin. Using these signals an average CO₂ concentration will be determined. Each gas sensor will sample the cabin air once every 10 seconds. Once the CO₂ concentration has been obtained the microprocessor will determine what action will be necessary. There are three primary modes of operation; CO₂ removal mode, power efficiency mode, and off mode.

CO₂ Removal Mode

When the concentration of cabin CO₂ exceeds the high level (Table 4.1-1) the computer will direct the removal system into the CO₂ removal mode. This mode uses a fixed half-cycle time increment similar to the current control system. However, this cycle-time will be derived with the idea of removing CO₂ from the cabin at the fastest rate possible. Because the ability of the desiccant bed system to remove CO₂ over time is an exponentially decaying function, it would be best to have a short cycle-time and switch the functions of the pairs of beds as rapidly as possible.

This time interval will be obtained using math modeling techniques, and information

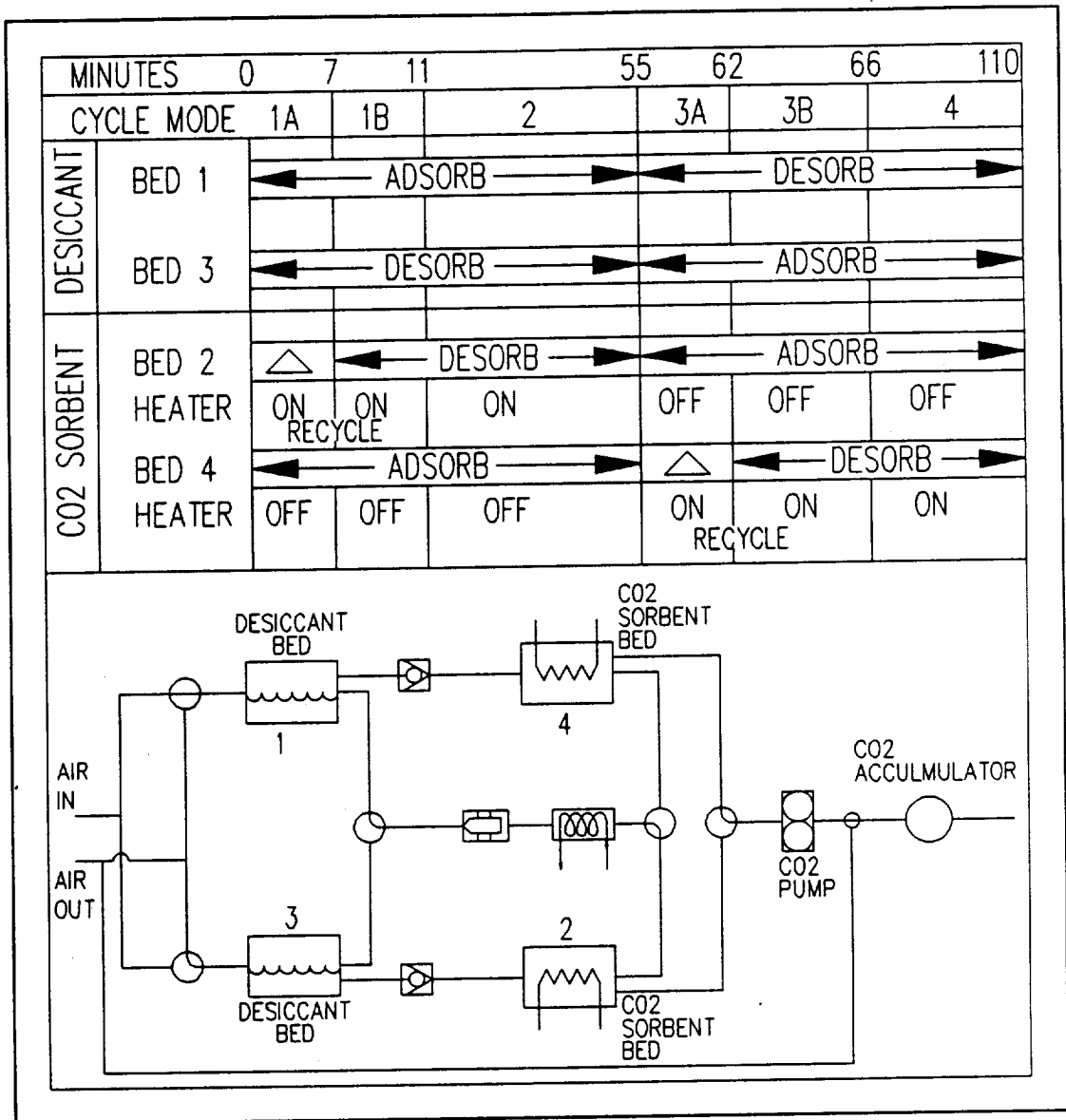


Figure 4.1-1. Four-Bed Operation as a Function of Time

about switching lags and set up times. In particular, the CO₂ adsorbent bed cool-down time as it relates to bed effectiveness, will be important. The goal will be to removal the greatest amount of CO₂ per unit time.

The mode would be used when large amounts of CO₂ are present in the cabin, for example, during astronaut exercise.

Power Efficiency Mode

When the level of cabin CO₂ is between the Hi and Lo levels indicated in Table 4.1-

1, the power efficiency mode would be activated. This mode uses a fixed half-cycle time which allows for adequate CO₂ removal, but minimizes the amount of electrical power used per unit of CO₂ removed. This time interval will be determined in a fashion similar to the manner in which the time interval for the CO₂ removal mode was found.

This mode will be useful when electrical power is limited on the station, for example, when a solar panel is damaged or a power shortage occurs.

Off Mode

During this operation the removal system will not be operating. This would allow astronauts to make repairs on the system.

Note: Before switching modes the computer will direct the system to clear all beds.

Table 4.1-1. CO₂ Operating Modes

Level	Mode	CO ₂ Concentration (ppm) *
Hi	CO ₂ Removal	≥ 1000
Lo	Power Efficiency	$300 < x < 1000$
Off		< 300

* Concentration levels were formulated using standard threshold limit values and information from Dr. Stephan Konz, Kansas State University.

SYSTEM MONITORING SCHEME

Below is a list of all the major system components. The sensor method is described for each component. This monitoring scheme will allow the system to be controlled, as outlined above, and also allow component failures to be detected. For each component the output of the sensor(s) will be compared with a desired output and error signal will be generated. The monitoring microprocessor, implementing an artificial intelligence program, will determine if a component failure has occurred. In the event of failure, the astronauts would be alerted via a computer terminal. Figure 4.1-2 is a pictorial of the system monitoring scheme.

Cabin - CO₂ gas sensors will be placed throughout the cabin to obtain an average CO₂ gas concentration. Using this information the microprocessor will select the appropriate operating mode for the CO₂ Removal System.

Air selector valves - These valves have end of position switches which can be used to determine if they have been completely switched into a valid position. This also allows the current position of the valve to be known.

Desiccant Bed - A humidity sensor will be placed just in front of the blower to measure the water content of the air stream. The system requires that a dew point of -70 °F be maintained for air entering the adsorbing adsorbent. This sensor will indicate if a desiccant bed has malfunctioned.

Blower - A pressure sensor will be placed in front of the blower and directly downstream from the blower to measure the pressure drop. A power sensor will be used to monitor the power consumed by the blower. Using the information from these sources it will be possible to determine if the blower is friction dragging, turning too slowly or otherwise failed.

Precooler - A temperature sensor will be placed on the air stream line after the precooler to determine if the air entering the adsorbing adsorbent bed is cool enough to allow for effective adsorption.

CO₂ Adsorbent Bed - A CO₂ gas sensor will be placed on the air-return-to-cabin pipe. By comparing the gas concentration at the bed exit with the gas concentration in the cabin it will be possible to determine if the bed is saturated or malfunctioning. A sensor will be used to monitor the power consumption of the adsorbent bed heater.

Check valve - An air-flow-rate sensor will be placed between the check valve and the CO₂ adsorbent bed to determine if the valve is leaking. The check valve assures that cabin air is not drawn directly into the system and stored in the CO₂ accumulator.

CO₂ Pump - A pressure sensor will be placed between the pump and the CO₂ selector valve. This sensor will allow leaks to be detected in the CO₂ selector valve, check valve, post precooler air select valve, and adsorbent bed. This sensor will also aid in monitoring the pump. The pumps power consumption will also be monitored using a sensor.

CO₂ Accumulator - An air-flow-rate sensor will be placed directly on both sides of the CO₂ Accumulator to allow leaks to be detected.

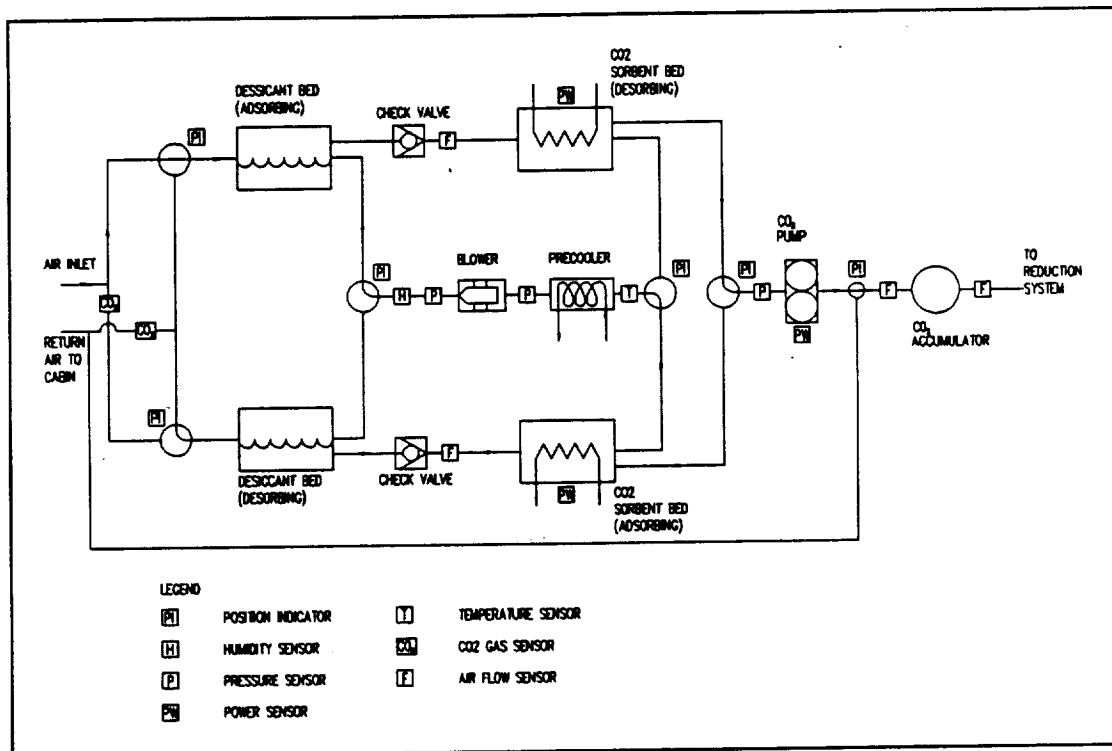


Figure 4.1-2. Proposed CO₂ Removal Sensor Locations

COMPARISON OF CONTROL SCHEMES

The new control scheme has several advantages over the current method. The primary advantage is that the new system has feedback. It operates on measured cabin CO₂ gas concentration. This allows the system to operate on a situational basis. The addition of three operating modes allows the new system to respond to different levels of CO₂ in the most effective manner. When CO₂ levels are high and threaten crew safety, the system will operate to remove CO₂ as rapidly as possible, with power consumption by the removal system being of secondary importance. When cabin CO₂ concentrations are between high and low, (Table 4.1-1) the CO₂ removal system will focus on power efficiency, freeing up power for higher priority needs. Finally the CO₂ removal system will be completely shut down if the cabin CO₂ level is very low.

The proposed control scheme has two main disadvantages over the old; it will be more complex and costly to implement. The new method will require a hardware study to determine the cycle times for the CO₂ removal and power efficiency modes. The cost of the new system monitoring scheme is also a drawback.

4.2 CO₂ REDUCTION CONTROL

CURRENT CONTROL SCHEME

The current control scheme used for the CO₂ Reduction Subsystem is a timing sequence for switching between two reactors. While one reactor is being operated, the other is cleaned of its carbon buildup and the catalyst is replaced. The reaction of CO₂ and H₂ in the functioning reactor is allowed to proceed for a specific amount of time before switching to the second reactor. The amount of time before switching occurs is determined by the size of the crew. For a detailed description of the CO₂ Reduction Subsystem, see the physical description portion of this document.

PROPOSED CONTROL SCHEME

The proposed control scheme is based upon increasing the efficiency of the reactors. Increasing reactor efficiency would allow less catalyst to be consumed. A reactor would be switched out of use when the efficiency of the reaction of CO₂ and H₂ drops below a set point. The efficiency is based upon four measured variables:

1. Composition of CO₂, H₂, CO, H₂O, and CH₄ in the subsystem.
2. Flow rate of the H₂O condensate out of the subsystem.
3. Flow rate of CO₂ and H₂ into the subsystem.
4. Relative humidity level in the subsystem.

SYSTEM MONITORING SCHEME

The gas composition sensor, flow rate sensors, and humidity sensor, shown in Figure 4.2-1, will collect data that can be used to calculate the efficiency of the subsystem. That data will be input into a microprocessor, which, by an appropriate algorithm, will compute the efficiency for the subsystem. The efficiency will be used to determine when a reactor will be switched out of operation and an alternate unit brought into use.

Monitoring the operation of the subsystem is an important part of a desirable control system. By implementing the following sensors shown in Figure 4.2-1: valve position sensor, tachometer, pressure sensors, and temperature sensors, action can be taken in case of emergency or system failure. The data collected from these sensors can be used by the microprocessor to detect problems that may be present in the subsystem. If the microprocessor detects a problem, the crew will be notified of the

possible complication and given instructions for corrective measures.

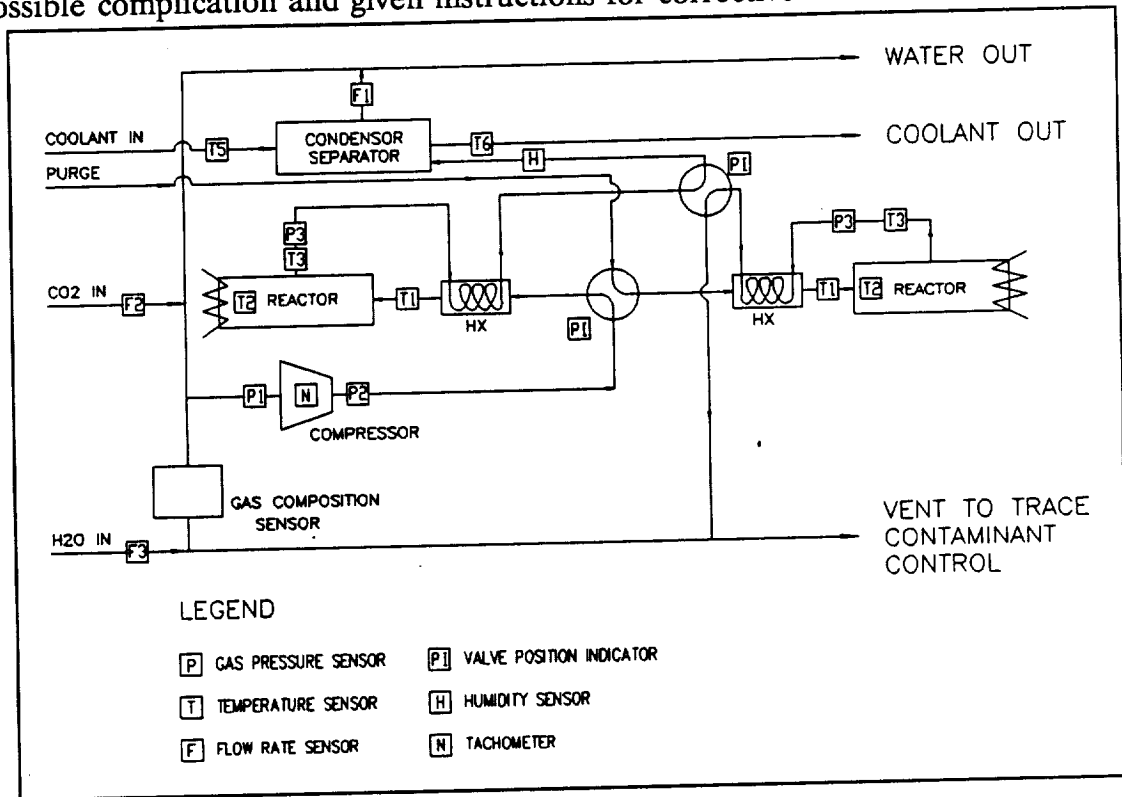


Figure 4.2-1. Proposed CO₂ Reduction Sensor Locations

Gas Composition Sensor

The type of gas sensor to be used is unknown at this time, but the sensor must meet several requirements:

1. Differentiate between CO₂, H₂, CO, H₂O, and CH₄.
2. Give the proportionality of the above gases.
3. Interface with a microprocessor.

This gas composition sensor is the most important feedback signal in the subsystem. It measures the proportionality, percent composition of air, CO₂, H₂, CO, H₂, and CH₄ currently in the subsystem. These measurements are sent to the microprocessor and, based on the levels of CO₂ and H₂ in the air, a return signal is sent to the inlet valves controlling the flow of CO₂ and H₂.

The flow rate sensors, F2 and F3, measure the rate at which CO₂ and H₂ flow into the subsystem. The amounts of CO₂ and H₂ gases added are dependent upon the composition of the recirculated gases already in the subsystem. When the reaction

is more efficient, larger amounts of CO_2 and H_2 are added to the system. When the efficiency of the subsystem declines, the amounts of CO_2 and H_2 added to the subsystem are less. The amounts of gas to be added depend upon the operating efficiency of the subsystem. F2 and F3 are also used as fault detection devices for the CO_2 Removal and OGA Subsystems. If CO_2 and H_2 were not present when needed by the CO_2 Reduction Subsystem, the sensors would recognize this and an error signal would be sent to the crew.

Compressor

The compressor is designed to operate at a constant speed, thus a tachometer will be incorporated to measure its speed. Gas pressure sensors, P1 and P2, placed at the input and output of the compressor, serve as another means of checking the rotational speed. If the pressures at P1 and P2 are not within an allowable percentage of each other, the compressor is not operating at the correct speed. If the rotational speed of the compressor is not correct, the crew will be notified of a problem.

Valves

The valves that switch the two reactors in and out of operation will be monitored to insure simultaneous switching. If the valves are not in the correct position, the subsystem may begin to malfunction. For example, if both valves are closed; a pressure increase will begin or if both valves are open; both reactors will be operating and a pressure drop will result. Therefore, if any drastic changes in pressure occur within the subsystem, the microprocessor will check these sensors for complications.

Bosch Reactor

The reaction of CO_2 and H_2 occurs within the Bosch Reactor. To insure that this reaction is proceeding properly, temperature sensors and a pressure sensor are used. Inside the Bosch Reactor, the gas temperature is measured to insure that the correct start-up temperature is provided. The input and output gas temperatures are also checked to be sure that the reaction proceeds at the proper rate. The pressure sensor, P3, placed on the output of the reactor will measure the gas pressure change caused by the increase in the gas temperature. This sensor will be referenced to P2 to make gas pressure differentiations.

Condenser/Separator

The condenser/separator is used to convert the gaseous H_2O into H_2O condensate, which is then allowed to flow out of the subsystem. This is accomplished by allowing a coolant to flow through this component. The coolant lowers the temperature of

the gaseous H_2O to its dew point, resulting in H_2O condensate. A humidity sensor, flow rate sensor, and temperature sensors are used to collect data for the microprocessor. A humidity sensor, H, will be used to measure the amount of gaseous H_2O in the subsystem. H_2O is a major product of the CO_2 Reduction Subsystem and the humidity in the subsystem is dependent on the efficiency of the reaction. The sensor, T4, located within the condenser/separator is used to measure the dew point. The input and output gas temperatures need to be known to guarantee that a proper coolant temperature is being maintained in order to condense the gaseous H_2O into a liquid state.

The flow rate sensor, F1, measures the rate at which H_2O condensate flows out of the subsystem. As the reaction occurs, solid carbon collects in the reactor, diminishing the efficiency of the process. This lower efficiency results in less H_2O being produced. Therefore, by measuring the rate at which H_2O condensate flows out of the subsystem, the efficiency of the reaction at a given time can be known by implementing the microprocessor's algorithm. If the flow rate out of the subsystem is not within a set of parameters, an error signal is reported to the crew.

COMPARISON OF CONTROL SCHEMES

The proposed control scheme will enhance crew safety by providing the astronauts with information detailing the operation of the subsystem. If a problem were to occur, the microprocessor would detect a change in the operation of the subsystem and notify the crew. In the current control scheme there is no monitoring devices within the subsystem. Therefore, no data pertaining to the subsystem operation is available to the crew.

Maximum subsystem efficiency is a very important consideration. In the current control scheme, the operation of the subsystem is continuous even when the efficiency of the reaction has decreased. This leads to increased power consumption. In the proposed control scheme the efficiency of the reaction is increased by collecting data from the sensors, then calculating the subsystem efficiency. When the subsystem efficiency drops below a set level the reactors are switched. By switching according to efficiency, the power consumption is reduced.

Finally, the crew's time spent watching the subsystem is minimized by implementing the microprocessor controls. The microprocessor will collect data from the subsystem and notify the crew when maintenance is required.

4.3 OXYGEN GENERATION ASSEMBLY

The production of oxygen is obviously a critical parameter for the survival of personnel in a controlled environment, such as on the Space Station Freedom (SSF). Therefore, it is crucial that the control of the OGA be precise, reliable, and efficient. A summary of the OGA's current control scheme, proposed control scheme, and discussion of measured variables is included in the following paragraphs. The summary of how the system operates can be reviewed in the AR System Overview section of this report.

CURRENT CONTROL SCHEME

The foundation for the control of the present OGA lies in the monitoring of the oxygen partial pressure in the space station cabin. The partial pressure is measured directly with the use of an oxygen partial pressure sensor. The value sensed is then compared to an acceptable range as outlined by NASA. The desired oxygen partial pressure operating range as well as other system parameters are listed in Table 4.3-1. If the partial pressure is too low, the current to the electrolysis module is increased which, in turn, increases the oxygen production rate. On the other hand, if the partial pressure is too high, the current to the electrolysis module is decreased to reduce the oxygen production rate.

Table 4.3-1. OGA Performance Requirements

Parameter	Units	Range
O ₂ Partial Pressure	kPa	20-23
Operating Pressure	kPa	1034-1379
O ₂ Delivery Pressure	kPa	104-172
H ₂ Delivery Pressure	kPa	138-206
H ₂ O Supply Pressure	kPa	207-300
O ₂ Delivery Rate (nom)	kg/day	4.12

The water tank which regulates the statically fed water to the electrolysis module is refilled every 3 hours. The process is simply initiated every 3 hours by a timing

The water tank which regulates the statically fed water to the electrolysis module is refilled every 3 hours. The process is simply initiated every 3 hours by a timing sequence within the system controller (4.3-1).

The actual control of the OGA is achieved using micro-processor based instrumentation. The present control package provides parameter control, automatic mode control, automatic self-protection shutdown, fault diagnostic functions and data acquisition interfacing. The Computer/Monitor Instrumentation (CMI) has accumulated hundreds of hours in performance and endurance testing to verify its designed operating and controlling characteristics (4.3-2).

PROPOSED CONTROL SCHEME

Many alternative control schemes were evaluated in an effort to discover a more efficient and/or productive method of controlling the OGA. However, none could be proven more effective than the current control scheme involving the monitoring of the O_2 partial pressure as the dominant control variable. Hence, the O_2 partial pressure monitoring should continue to be the governing variable upon which the OGA control scheme is based. However, a few minor changes to improve system efficiency, flexibility, and safety are proposed as follows.

First, the controller could be enhanced by incorporating an additional system operating mode based on subsystem efficiency. The current controller has both a normal and an emergency operating mode. The emergency operating mode has a much higher O_2 production rate than the normal mode to facilitate most crisis situations. The production rate increase is initiated by an increase in the current to the electrolysis module. Therefore, the addition of an efficiency operating mode would expand the flexibility of the OGA. The efficiency mode would operate near the minimum oxygen partial pressure requirement, thus reducing the electrolysis module current requirement. This mode could be utilized during sleeping hours or if power consumption were to become a critical factor.

A further system improvement involves the fill cycle for the water storage tank. Rather than simply initiating the fill cycle every 3 hours, a level sensor placed in the water tank could be utilized to provide feedback to indicate when the tank needs to be filled. This would reduce the number of fill cycles required on a daily basis, therefore reducing the power consumed in the operation of the fluid control valves.

Other recommendations involve the utilization of sensors for system monitoring and fault detection. The present OGA sensors allow for a wide range of fault detection, fault isolation, and fault prediction. However, a few sensor additions could help improve the system's ability to detect and analyze a possible system failure. The recommended sensor additions are defined and discussed in the following section.

SYSTEM MONITORING SCHEME

The following information outlines the variables to be monitored or currently being monitored within the cabin and each of the major subassemblies of the OGA. The general sensor locations are shown in Figure 4.3-1.

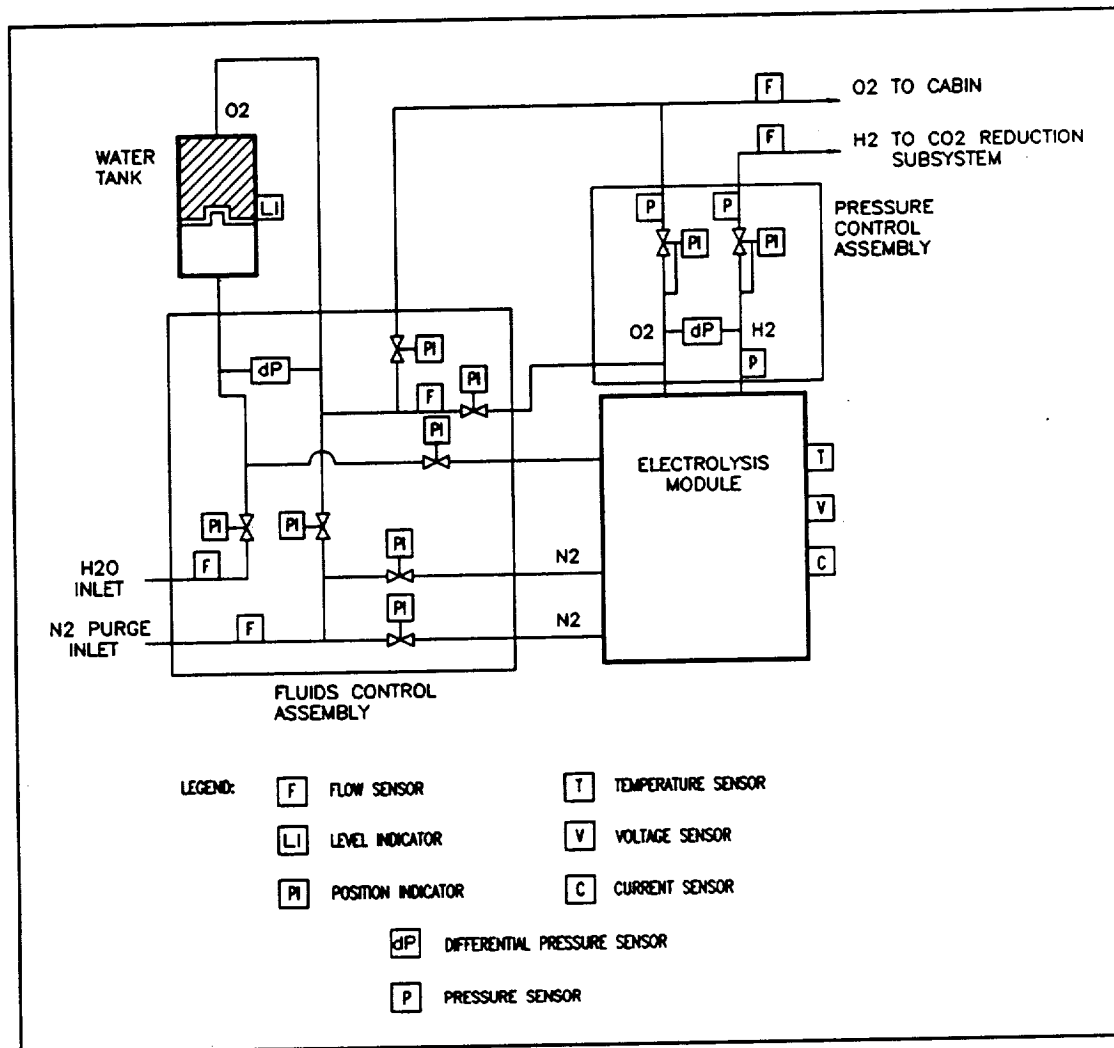


Figure 4.3-1. Proposed OGA Sensor Locations

Cabin - The O₂ partial pressure sensor is the only sensor required in the cabin area. Multiple sensors should be strategically placed in throughout the cabin and their readings averaged to allow for an accurate recording of the actual partial pressure.

Electrolysis Module - Temperature (T), current (C), and voltage (V) sensors are utilized in the electrolysis module. These sensed values allow for the calculation of

the module's efficiency as well as fault detection and diagnosis.

Fluid Control Assembly (FCA) - The valves within the FCA each contain an electronic position indicator for verification of the valve position before and after an operating mode has been initiated. This helps to prevent a valve failure from causing system damage and to facilitate quicker failure diagnosis if an automatic system shutdown were to occur. Water, oxygen, and nitrogen flow valves are also employed so that their respective fluid consumption or utilization rates can be monitored. The pressure differential between the water in the water tank and the oxygen supplied to the water tank is monitored to detect any erroneous pressure differences during water tank fill and static feed cycles.

Pressure Control Assembly (PCA) - The PCA contains two electronic pressure regulators with electronic position feedback, a differential pressure sensor, and a hydrogen pressure sensor. One regulator controls the hydrogen production pressure while the other regulator controls the difference between the O_2 and H_2 production pressures. It is assumed that the electronic regulators also contain pressure sensors built into their design to facilitate monitoring of the OGA H_2 and O_2 output pressures. Flow rate sensors are not currently utilized to monitor the oxygen and hydrogen production rates. Therefore, it is recommended that they be installed and monitored to provide an indication of the system capacity and efficiency. All measured variables can also be monitored periodically for fault detection and fault avoidance.

Water Storage Tank - Presently, no variables are sensed in the water storage tank. However, as mentioned previously, an electronic water tank level indicator is recommended to facilitate the proposed control of the tank fill cycle.

COMPARISON OF CONTROL SCHEMES

The basic control strategies of the current control system and the recommended control system are the same. The O_2 partial pressure will continue to be the governing variable by which the OGA will be controlled. However, the proposed CMI efficiency mode and water tank level indicator can help to reduce overall system power consumption during non-critical hours. Also, the recommended sensor additions allow for better fault prediction, fault detection, and fault isolation. These suggested improvements can help to make the OGA a more productive and efficient system which, in turn, can help to improve the efficiency of the Atmosphere Revitalization assembly.

5.0 MATHEMATICAL MODELING

5.1 CARBON DIOXIDE REMOVAL

FOUR BED MOLECULAR SIEVE

Component Description - The CO₂ removal bed modeled is shown in Figure 5.1-1. It consists of a shelf type arrangement that is packed with sieve material and retained on each end by a screen. It also contains an electric heating element that is used for increasing the bed temperature during desorption. The canister in which the sieve material is packed is of a double wall construction with a vacuum between the walls to reduce heat loss to the surroundings.

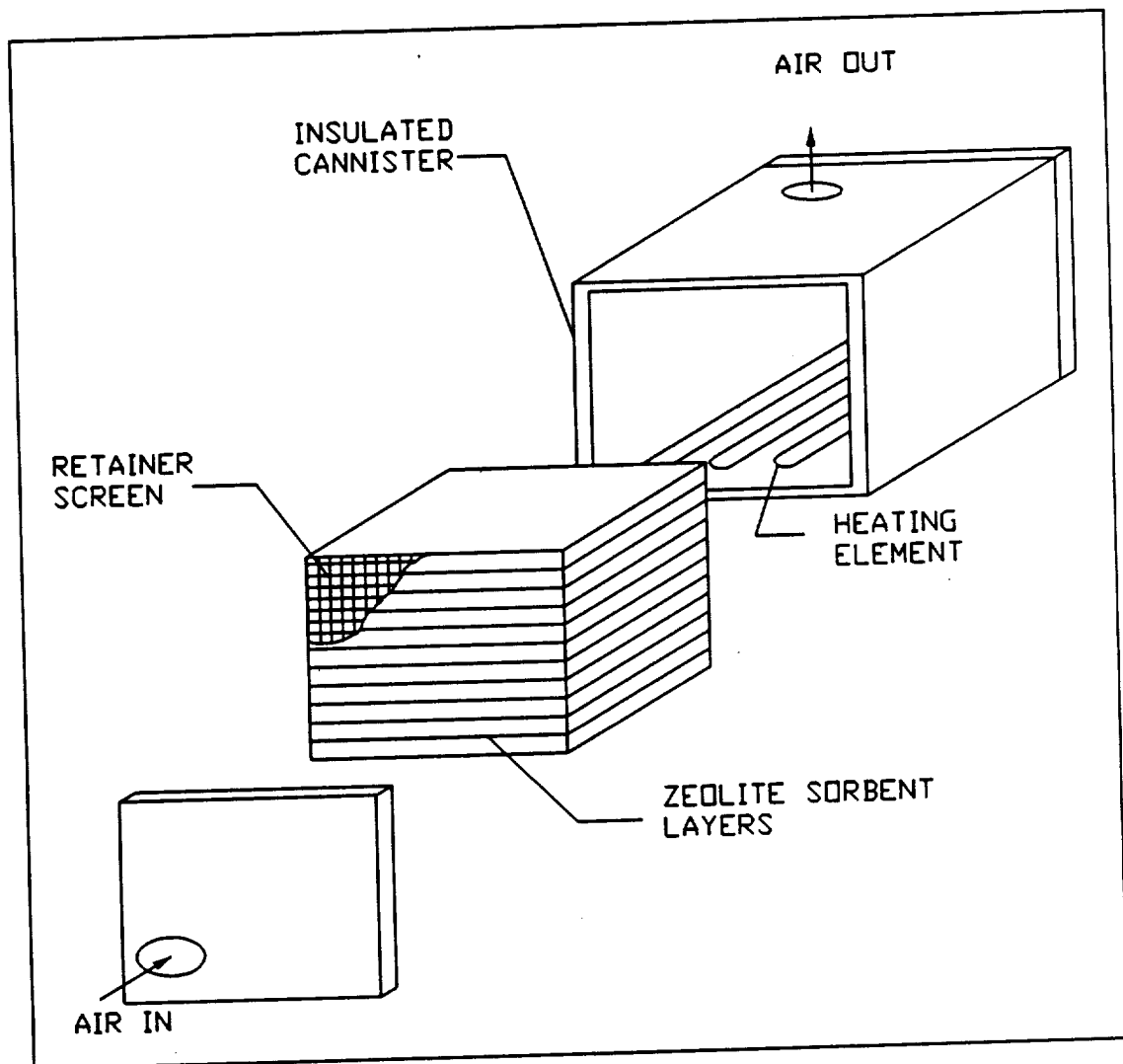


Figure 5.1-1. Modeled CO₂ Removal Bed

Physical Operation - The physical operation consists of CO_2 laden air being pumped into the canister, and while passing through, some of the CO_2 is trapped within the bed. This "trapping" of CO_2 gives off energy in a manner similar to that released by a phase change from gas to liquid. This energy is then absorbed by the remaining gas, sieve material and canister. Since the heat is being generated by the adsorption process, the rate at which this process takes place is critical in determining the energy and mass balances for the CO_2 .

Adsorption and desorption from the sieve material depends on many things including the size of the sieve material pores and the size of the molecules trying to adsorb or desorb. The adsorption and desorption involve a series of mass transfer steps.

Removal of CO_2 and H_2O from the incoming air stream is very similar in the physics that govern each, therefore we will model them the same way. Because of this, the rest of the paper discusses CO_2 removal and the use of Zeolite 5A exclusively.

Adsorption:

1. The CO_2 diffuses from the bulk fluid (incoming air stream) to the external surface of the catalyst pellet.
2. The CO_2 then diffuses from the pore mouth through the catalyst pores to the immediate vicinity of the internal zeolite surface.
3. The CO_2 then adsorbs into the zeolite surface.

Desorption:

1. The bed is heated. This heating causes the forces of attraction between the zeolite surface and the CO_2 molecule to weaken and the CO_2 molecule to desorb.
2. The CO_2 molecules diffuse from the interior of the pellet to the pore mouth at the external surface.
3. The CO_2 molecules diffuse from the external pellet surface to the bulk fluid.

The CO_2 adsorption and desorption processes are governed primarily by the overall pressure in the bed, the partial pressure of the CO_2 and the equilibrium vapor pressure at the surface of the zeolite. For the adsorption process, the temperature of the bed should not vary significantly enough to cause the mass transfer coefficient to vary and will therefore be considered constant. During the desorption phase, the

mass transfer coefficient will be determined from empirical data.

Assumptions

1. Sieve material can be represented by spherical particles for mass transfer calculations and are assumed to be isothermal.
2. Adsorption occurs by the diffusion of an adsorbate through a stagnant film at the zeolite's surface and then diffuse into the interior of the zeolite particle. Desorption occurs in a reverse manner.
3. Heat of adsorption and desorption are constant.
4. Bed properties vary only in the direction parallel to the air flow.
5. The time required for a control volume of air to pass through the bed is much shorter than the time required for any significant rise in either the bed loading, adsorbent temperature, or canister temperature. Therefore the temperature of the air and the pressure drop of the air can be modeled as quasi-steady state functions where both are only a function of axial distance from the inlet of the bed.
6. Alternatively, the bed loading and temperature of the container and the sieve material are time dependent.

ENERGY, MASS AND PRESSURE BALANCES

Energy Balance Equation for the Gas Stream.

Equation (5.1-1) predicts the temperature of the air at any point in the bed as a function of distance from the inlet. It is assumed that the air is passing through the bed at a much faster rate than either the adsorbent or the canister are heating up (ie. the concept of quasi-steady state). The following equations were developed originally by K. C. Wuang, Airesearch Simulation Program (5.3-1) and have been modified to fit the current adsorbent bed configuration. The current bed configuration differs from that used in the Airesearch Simulation by having the H₂O removal bed and the CO₂ removal beds separated into two different canisters. The original model had the two sieve materials contained in the same canister and separated only by a screen. It was also assumed that the heat transfer to the surroundings was negligible but could be added later with the addition of another term. The energy balance gives

$$\frac{dT_g}{dx} = \frac{1}{f \cdot \rho_g \cdot C_{pg} \cdot U_g} \cdot [(A_{sg} \cdot H_{sg}) \cdot (T_s - T_g) + (A_{xg} \cdot H_{xg}) \cdot (T_x - T_g)] \quad (5.1-1)$$

where $T_g = T_s$ at $x = 0$ for absorption and $T_g = T_{gi}$ at $x = x_0$ for desorption.

The introduced variables are defined as follows:

T_g = Temperature of the gas (K) ,

f = Void fraction of the bed (dimensionless) ,

ρ_g = Density of the gas (kg/m³) ,

C_{pg} = Heat capacity of the gas (J/kg·K) ,

U_g = Interstitial gas velocity (m/hr) ,

A_{sg} = External surface area of sorbent (m²/m³) ,

H_{sg} = Heat transfer coef. of sorbent and gas based on
 A_{sg} (J/m²·K·hr) ,

H_{sg} - Heat transfer coef. of sorbent and gas based on A_{sg} ($J/m^2 \cdot K \cdot hr$),

T_s - Temperature of the sorbent (K),

A_{xg} - Heat exchanger - gas contact area (m^2/m^3),

H_{xg} - Heat transfer coefficient of the heat exchanger with the gas based on A_{xg} ($J/m^2 \cdot K \cdot hr$),

T_x - Heat exchanger core metal temperature (K).

The energy Balance Equation for Zeolite Adsorbent has the form

$$\frac{dT_s}{dt} = \frac{1}{c_{ps} \cdot \rho_{sb}} \left[\frac{\partial}{\partial x} \left(K_s \cdot A \cdot \frac{\partial T_s}{\partial x} + (A_{sg} \cdot H_{sg}) \cdot (T_g - T_s) + (A_{xg} \cdot H_{xg}) \cdot (T_x - T_s) + (A_{sg} \cdot K_g) \cdot (P_k - P_{ks}) \cdot DH_k \right] \right. \quad (5.1-2)$$

where $\frac{\partial T_s}{\partial t} = 0$ at $x=0$ and $x=x_0$.

Here the variables are defined as

c_{ps} - Heat capacitance of the sorbent ($J/kg \cdot K$),

ρ_{sb} - Sorbent bulk density (kg/m^3 of bed),

K_s - Effective thermal conductivity of zeolite sorbent ($J/hr \cdot m^2 \cdot K \cdot m$),

A - Cross-sectional area of bed (m^2),

A_{sg} - External surface area of sorbent (m^2/m^3 of bed),

H_{sg} - Heat transfer coefficient between sorbent and gas,

based on A_{sg} ($J/m^2 \cdot K \cdot hr$).

T_g - Gas temperature (K).

T_s - Sorbent temperature (K).

T_x - Core metal temperature (K).

K_g - Mass transfer coefficient between bulk stream and the surface of the adsorbent. Surface kinetic rate can be

incorporated in the coefficient ($kgmol/hrm^2 \cdot mmHg$).

DH_k - Heat of adsorption of CO_2 (J/kg adsorbed).

P_k - Partial pressure of CO_2 in the gas stream ($mmHg$).

P_{ks} - Equilibrium surface vapor pressure ($mmHg$).

The energy Balance Equation for the Core Metal can be written as

$$\frac{dT_x}{dt} = \frac{1}{c_{px} \rho_x} \cdot \left[\frac{\partial}{\partial x} \left(K_x A \cdot \frac{\partial T_x}{\partial x} \right) + A_{vx} \cdot [H_{xs} \cdot (T_s - T_x) + H_{xg} \cdot (T_g - T_x)] \right], \quad (5.1-3)$$

where

$T_x = 0$ at $x=0$ and $x=x_0$.

The following definitions are needed:

c_{px} - Heat capacitance of core metal ($J/kg \cdot K$),

ρ_x - Heat exchanger core metal density (kg/m^3),

K_x - Thermal conductivity of core metal ($J/hr \cdot m^2 \cdot K \cdot m$),

A_{vx} - Primary heat transfer area for core metal
(m^2/m^3 of metal),

H_{xs} - Effective heat transfer coefficient between core metal
and sorbent material ($J/m^2 \cdot K \cdot hr$),

H_{xg} - Effective heat transfer coefficient between core metal
and gas ($J/m^2 \cdot K \cdot hr$),

T_x - Core metal temperature (K),

T_s - Zeolite sorbent temperature (K),

T_g - Gas temperature (K).

Temperature Transfer Equation For The CO_2 Removal Bed

Using equation 5.1-1 (same as 5.1-4) and assuming a quasi-steady state relationship between time and the gas temperature with all variables in the equation independent

of X, the equation is separable. Integrating over each respective variable range will yield the change in temperature of the incoming air. The following equation repeats Eq. 5.1-1 for convenience.

$$\frac{dT_g}{dx} = \frac{1}{f \cdot \rho_g \cdot C_{pg} \cdot U_g} \cdot [A_{sg} \cdot H_{sg} \cdot (T_s - T_{gi}) + A_{xg} \cdot H_{xg} \cdot (T_x - T_{gi})] \quad (5.1-4)$$

The heat transfer by conduction through the adsorbent and the metal core has been assumed to be negligible and have been dropped in order to simplify the integrations. First let

$$C_1 = \frac{A_{sg} \cdot H_{sg}}{f \cdot \rho_g \cdot C_{pg} \cdot U_g} \quad \text{and} \quad C_2 = \frac{A_{xg} \cdot H_{xg}}{f \cdot \rho_g \cdot C_{pg} \cdot U_g}$$

then form the following integrations:

$$\frac{dT_g}{dx} = (C_1 \cdot T_s - C_1 \cdot T_{gi}) + (C_2 \cdot T_x - C_2 \cdot T_{gi}) \quad (5.1-5)$$

$$\int dT = \int C_1 \cdot T_s \cdot dx - \int C_1 \cdot T_{gi} \cdot dx + \int C_2 \cdot T_x \cdot dx - \int C_2 \cdot T_{gi} \cdot dx \quad (5.1-6)$$

$$T = (C_1 \cdot T_s - C_1 \cdot T_{gi} + C_2 \cdot T_x - C_2 \cdot T_{gi}) \cdot x + b_0 \quad (5.1-7)$$

$$T_2 - T_1 = C_1 \cdot (T_s - T_{gi}) \cdot L + C_2 \cdot (T_x - T_{gi}) \cdot L + b_0 \quad (5.1-8)$$

Differentiating both sides with respect to time and holding the incoming air temperature constant, yields

$$\frac{d}{dt} (T_{out} - T_{in}) = \frac{d}{dt} (C_1 \cdot T_s \cdot L - C_1 \cdot T_{gi} \cdot L + C_2 \cdot T_x \cdot L - C_2 \cdot T_{gi} \cdot L + b_0) \quad (5.1-9)$$

This can be written as

$$\frac{dT_{out}}{dt} = C_1 \cdot L \cdot \frac{dT_s}{dt} + C_2 \cdot L \cdot \frac{dT_x}{dt} \quad (5.1-10)$$

When C_1 and C_2 are substituted, one obtains the equation

$$\frac{dT_{out}}{dt} = \frac{A_{sg} \cdot H_{sg} \cdot L}{f \cdot \rho_g \cdot C_{pg} \cdot U_g} \cdot \frac{dT_s}{dt} + \frac{A_{xg} \cdot H_{xg} \cdot L}{f \cdot \rho_g \cdot C_{pg} \cdot U_g} \cdot \frac{dT_x}{dt}, \quad (5.1-11)$$

where dT_s and dT_x are given by Equations 5.1-2 and 5.1-3, respectively.

MASS BALANCES

Diffusion Equation for Interior of Adsorbent Pellet

This equation gives the rate at which material (either carbon dioxide or water) is adsorbed onto zeolite particles. Before deriving this equation, it is first necessary to consider the three resistances to mass transfer in this system (5.1-2). The first of these is a gas film resistance. The gas film is a very small area immediately above the zeolite particle. The resistance occurs because the pressure in this area is greater than that in the passing gas stream. Second, is a bulk resistance. Gas molecules meet this type of resistance when they diffuse through the interior pores of the zeolite particles. The third type of resistance must be considered a reaction resistance. This resistance would be encountered if there were a reaction in the adsorbing process. However, there is no reaction in this system, so there is no reaction resistance. Thus, the first two types of resistances are encountered in the adsorbing system. Gas film resistance is accounted for in one of the boundary conditions, while bulk resistance is accounted for in the material balance.

The diffusion equation can be derived from the equation of continuity in spherical coordinates which gives the bulk resistance in terms of mass diffusivity. Simplification of it yields

$$\frac{dc_k}{dt} = \frac{D_k}{r^2} \cdot \frac{d}{dr} \left(r^2 \cdot \frac{dc_k}{dr} \right), \quad (5.1-12)$$

where the following definitions are required:

c_k - molar concentration of species k (moles/m³),

t - time from start of adsorption/desorption cycle (hr),

D_k - mass diffusivity of component k through the interior

of the sorbent (m²/hr),

r - radial distance from center of catalyst sphere (m).

Putting this equation in terms of mass units yields

$$\frac{dW_k}{dt} = \frac{D_k}{\rho_s \cdot r^2} \cdot \frac{d}{dr} \left(r^2 \cdot \frac{dW_k}{dr} \right) \quad (5.1-13)$$

with definitions:

ρ_s - sorbent density (kg/m³ particle),

W_k - loading of component k in sorbent (kgsorbate/kg sorbent).

There are two boundary conditions necessary to solve this equation. The first simply states that no gas is adsorbed at the entrance to the bed (i.e. at $r = 0$). The second introduces the film resistance. This resistance is proportional to the mass transfer coefficient of the system times the difference in the gas stream pressure and the equilibrium surface vapor pressure. The conditions are given as

$$\frac{dW_k}{dr} = 0 \quad \text{at } r = 0 \quad (5.1-14)$$

and

$$-\rho_s \cdot D_k \cdot \frac{dW_k}{dr} = M_k \cdot K_g \cdot (P_{ks} - P \cdot X_k) \quad \text{at } r = r_s, \quad (5.1-15)$$

and the following notes are required:

M_k - molecular weight of component k (kg/kgmol),

K_g - mass transfer coefficient between the bulk stream and

the surface of the adsorbent (kgmol/m²·Pa·hr),

P_{ks} - equilibrium surface vapor pressure (Pa),

P - total system pressure during adsorption (Pa),

X_k - mole fraction of component k in the gas stream,

r_s - average particle radius (m) .

Adsorption Material Balance Equation for One of the Components (the k -th component) in the Gas Stream

Two things are assumed in the development of this equation. One, there is no axial diffusion and two that quasi-steady-state conditions exist for the gas phase material balance. This equation is derived by starting with the general material balance equation given as

$$\text{Rate of Accumulation} = \text{Rate}_{\text{in}} - \text{Rate}_{\text{out}} + \text{Rate}_{\text{Generation}} \quad (5.1-16)$$

The rate in and out terms can be expressed in terms of the partial pressures of component k . During the adsorption process, mass is transferred from the gas stream to the zeolite surface at a rate proportional to the mass-transfer coefficient of the system. The symbolic equation takes the form

$$0 = \frac{P_k}{X} - \frac{P_k}{X + \Delta X} - \frac{K_g \cdot a_{sg} \cdot M_g \cdot P}{f \cdot U_g \cdot (P_k - P_{ks}) \cdot \Delta X}, \quad (5.1-17)$$

where the following definitions apply:

P_k - $P \cdot X_k$ - partial pressure of component k in the bulk

gas stream (Pa) ,

M_g - average molecular weight of the process gas (kg/kgmol) ,

f - void fraction of bed,

ρ_g - gas density (kg/m³) ,

x -distance from molecular sieve bed end (m) ,

U_g -interstitial gas velocity (m/hr) ,

a_{sg} -external surface area of absorbent (m^2/m^3 of bed) .

After dividing by Δx and taking the limit as Δx goes to infinity, one obtains

$$\frac{dP_k}{dt} = \frac{P \cdot M_g \cdot a_{sg} \cdot K_g \cdot (P_{ks} - P_k)}{f \cdot \rho_g \cdot U_g} \quad (5.1-18)$$

The initial condition necessary to solve this equation is

$$P_k = P_{k(inlet)} \text{ at } x = x_0 \quad (5.1-19)$$

PRESSURE BALANCES

Pressure Equation for Desorption

This equation is transient and allows the bed pressure to be calculated at any bed location at any time. To accomplish this, a mass balance must be written over a unit volume of the bed. Unlike the above balance, this one depends on time since the pressure drop being modeled depends on time. Again, the generation term is a function of the rate of mass-transfer between the gas stream and the zeolite particle. This balance is done in terms of molality and takes the form

$$A \cdot f \cdot \frac{dc}{dt} = - \frac{d}{dx} (f \cdot C \cdot A \cdot U_g) + A \cdot M_{sg} \quad (5.1-20)$$

where one needs to define the following:

A - Cross-sectional area of adsorbent bed (m^2) ,

C - Molal density of the gas mixture ($kgmol/m^3$) ,

M_{sg} - Molal rate of mass transfer into the bulk fluid per unit
of bed volume ($\text{kgmol/hr}\cdot\text{m}^3$ of bed) .

The symbol M_{sg} can also be written as

$$M_{sg} = a_{sg} \cdot K_g \cdot (P_{ks} - P \cdot X_k) .$$

The gas velocity U_g is related to the pressure gradient by

$$U_g = - \frac{1}{F \cdot \frac{dP}{dx}} , \quad (5.1-21)$$

where F = a function of pressure.

The molal density can also be determined from the ideal gas law. This development gives

$$PV = nRT \quad (5.1-22)$$

with the following definitions:

V - volume of gas (m^3) ,

n - number of moles (mol) ,

R - ideal gas constant ($\frac{\text{kg}\cdot\text{m}^2}{\text{s}^2\cdot\text{kgmol}\cdot\text{K}}$) ,

T - gas temperature (K) ,

$$C = \frac{n}{V} = \frac{P}{R \cdot T} , \quad (5.1-23)$$

Differentiating equation (5.1-23) yields

$$\frac{dC}{dt} = \frac{1}{R \cdot T_g} \cdot \frac{dP}{dt} - \frac{P}{R \cdot T_g^2} \cdot \frac{dT_g}{dt}, \quad (5.1-24)$$

where

T_g = gas temperature (K).

If equations (5.1-21), (5.1-23) and (5.1-24) are combined into equation (5.1-20) and the second term of equation (5.1-24) is dropped, a quasi-isothermal equation results of the form

$$\frac{dP}{dt} = \frac{P}{F} \cdot \frac{d^2P}{dx^2} + \frac{P}{f \cdot C \cdot A} \cdot \frac{d}{dx} \left(\frac{f \cdot C \cdot A}{F} \right) \cdot \frac{dP}{dx} + \frac{P \cdot M_{sg}}{f \cdot C}. \quad (5.1-25)$$

Equation (5.1-25) is the equation needed to calculate the pressure changes during the desorption half-cycle. It is subject to the boundary condition

$$\frac{dP}{dx} = 0 \quad \text{at } x = 0. \quad (5.1-26)$$

This boundary condition says that the pressure is not changing with the length of the reactor at the entrance to the desorbing bed.

Thus far, nothing has been said about how the proportionality constant F is to be found. This determination can be done empirically. Equation (5.1-21) shows that F is strongly dependent on pressure. The value of F at different pressures for the flow of nitrogen through a 5/8"-I.D. molecular sieve bed can be found by reducing pressure drop data using equation (5.1-27) as

$$F(N_2) \frac{G \cdot R \cdot T_g}{M_g} = \frac{(P_1^2 - P_2^2)}{2 \cdot (x_2 - x_1)}, \quad (5.1-27)$$

where

G = mass flux = $U_g \cdot \rho_g$, kg/hr/m² of void area

and

R = ideal gas constant, $\frac{\text{kg} \cdot \text{m}^2}{\text{s}^2 \cdot \text{kgmol} \cdot \text{K}}$.

The results can then be plotted. A best fit line through the data points gives

$$F(N_2) = 2.494 \text{ EX } 10^{-4} \cdot P^{0.795}. \quad (5.1-28)$$

The problem with equation (5.1-28) is that it is only applicable for nitrogen gas at 70°F. The viscosity of nitrogen at this temperature is 0.0174 cp. To linearly correct for the differences in viscosity, the Blake-Kozeny equation can be used. (5.1-2) This leads to the equation with the definitions:

v_0 - superficial velocity, m/hr,

$$v_0 = \frac{P_0 - P_1}{L} \cdot \frac{D_p^2}{150 \cdot \text{viscosity}} \cdot \frac{f}{(1-f)^2}, \quad (5.1-29)$$

D_p - spherical particle diameter (m),

L - length of desorbing bed (m),

viscosity - viscosity of gas (kg/m/hr).

Combining equations (5.1-28) and (5.1-29) yields

$$F = 2.494 \text{ EE } 10^{-4} \cdot \left(\frac{\text{avg. viscosity}}{0.0174} \right) \cdot P^{0.795}. \quad (5.1-30)$$

CONCLUSIONS

Writing mass and energy balances can be quite difficult. There are a couple of important points that one should consider before beginning to write the balances. The first is that no analytical balance is going to exactly model a "real world" system. Therefore, if even a simple equation, can be used in a simulation. This way, you have a model, whether good or bad, that you can put into your simulation and see how it interacts with the other components in the system. Use the faculty members as needed. They are here to help students so bounce ideas off of them or have them check your work to see if you are doing something correctly.

While unsteady-state balances are often hard to derive, they are what really describes the system. No steady-state equation can model the time dependence of the system. For example, the amount of carbon dioxide which is adsorbed onto the adsorbent material is a function of time. A steady-state equation (i.e. one that would give the adsorbing rate as being constant) would not be correct as it does not account for the fact that the amount of carbon dioxide adsorbed decreases as time increases.

The first attempt at determining the mass and energy balances describing the four bed molecular sieve system were simple mass and energy balances. This yielded some equations, which as it turned out, were not really correct. However, it was a start and would have given us something to simulate using EASY5. After a couple of months working on the balances, the design team received a copy of a program written by Airesearch Manufacturing Company which NASA uses to model their four bed molecular sieve. This program included the mass and energy balances presented above. The design team then worked to understand the given equations and to derive them from fundamental principles (i.e. conservation of mass and energy).

HEAT EXCHANGER (PRECOOLER)

Description

The precooler is a stainless steel cross flow heat exchanger with double pass liquid coolant. The liquid coolant is water that enters the cooler at approximately 278.71 K. Dehydrated process-air enters the chamber with a temperature of 355.38 K.

Details Of Operation

The hot process-air gives off heat to the stainless steel casing, lowering the temperature of the process-air and raising the temperature of the stainless steel. The stainless steel in turn, gives off heat to the liquid coolant lowering the temperature of the stainless steel and raising the temperature of the coolant. The temperature of the stainless steel casing adjusts until the heat gained from the hot air equals the heat lost to the coolant. This adjustment in temperature is the transient response of the heat exchanger. There is also some heat transferred from the heat exchanger to the room. However, the heat is transferred through conduction and free convection processes which are much less effective than the forced convection process inside the heat exchanger. Therefore heat transfer to the surroundings is neglected. The pressure, mass flow, and composition of the process air do not change in the heat exchanger.

Assumptions

1. Heat transfer to the surroundings is negligible. The processes of heat transfer to the surroundings, conduction and free convection, are much less efficient than the forced convection inside the heat exchanger, thus accounting for a very small amount of the total heat lost. In addition, the temperature differential between the heat exchanger and the surroundings is much less than the changes in temperatures within the cooler. Finally, the liquid coolant has a much higher convection heat transfer coefficient than the air surrounding the component.
2. Pressure drop across the heat exchanger is negligible. The area of the coolant cross flow pipes is small compared to the area of the heat exchanger. This small obstruction will not cause a large pressure change.
3. The coolant reservoir is large (the coolant entrance temperature is constant). There will be sensitive equipment on the space station which will require a large heat sink to maintain a constant coolant temperature, so NASA will have no choice but to equip the Station with a large enough reservoir so that large temperature fluctuations do not occur.

4. The process-air flows through the heat exchanger rapidly in comparison to the heat exchanger's cycle time. This assumption is made based on the test data received from NASA.

Derivation Of Equations

The heat transfer rate is the amount of heat transfer from one object to another object and is represented by

$$Q = U \cdot A \cdot (T_1 - T_2), \quad (5.1-31)$$

with the definitions:

$U \cdot (T_1 - T_2)$ is the heat flux,

A - area of contact (m^2),

U - overall heat transfer coefficient, ($W/m^2 \cdot K$),

T_1 - temperature of area one, (K),

T_2 - temperature of area two, (K).

In this system there is heat transfer from the hot air to the heat exchanger and from the heat exchanger to the liquid coolant. These processes are represented by the following equations:

$$Q_{a-hx} = U_1 \cdot A_1 \cdot (T_{a,i} - T_{ex})$$

and

$$Q_{hx-w} = U_2 \cdot A_2 \cdot (T_{ex} - T_{w,i}).$$

Here the required definitions are:

Q_{a-hx} - heat transfer rate from air to heat exchanger (W),

Q_{hx-w} - heat transfer rate from heat exchanger to water (W),

U_1 - heat transfer coef. between air and stainless steel
[$(W/m^2) \cdot K$],

U_2 - heat transfer coef. between stainless steel and water
[$(W/m^2) \cdot K$],

A_1 - area between air and heat exchanger (m^2),

A_2 - area between heat exchanger and water (m^2),

$T_{a,i}$ - hot air inlet temperature (K),

T_{ex} - temperature of the stainless steel (K),

$T_{w,i}$ - cold water inlet temperature (K).

The change in temperature of the stainless steel is the heat remaining in the component divided by the heat capacity of the component. This is represented by

$$\frac{dT}{dt} = \frac{Q_{a-hx} - Q_{hx-w}}{\dot{m}c_p}, \quad (5.1-32)$$

where

$\frac{dT}{dt}$ - change in temperature of the system (K)

and

$\dot{m}c_p$ - heat capacity of the system ($J/s \cdot K$).

The change in the temperature of the heat exchanger is the old temperature of the heat exchanger plus the change in temperature from above. This gives

$$T_{ex}(new) = T_{ex}(old) + \frac{dT}{dt} \cdot \Delta t \quad (5.1-33)$$

with definitions

$T_{ex}(new)$ - temperature at the present time (K) ,

$T_{ex}(old)$ - temperature at the present time minus Δt (K) ,

Δt - time increment (s) .

Time Response of the Heat Exchanger

A computer model of a heat exchanger was implemented using the equations developed. The system response is greatly dependent on the characteristics of the particular heat exchanger. The values for U_1 , U_2 , A_1 and A_2 are unknown at this time. However, estimates were made, and as Figure 5.1-2 indicates, the system reached steady state within 12 seconds.

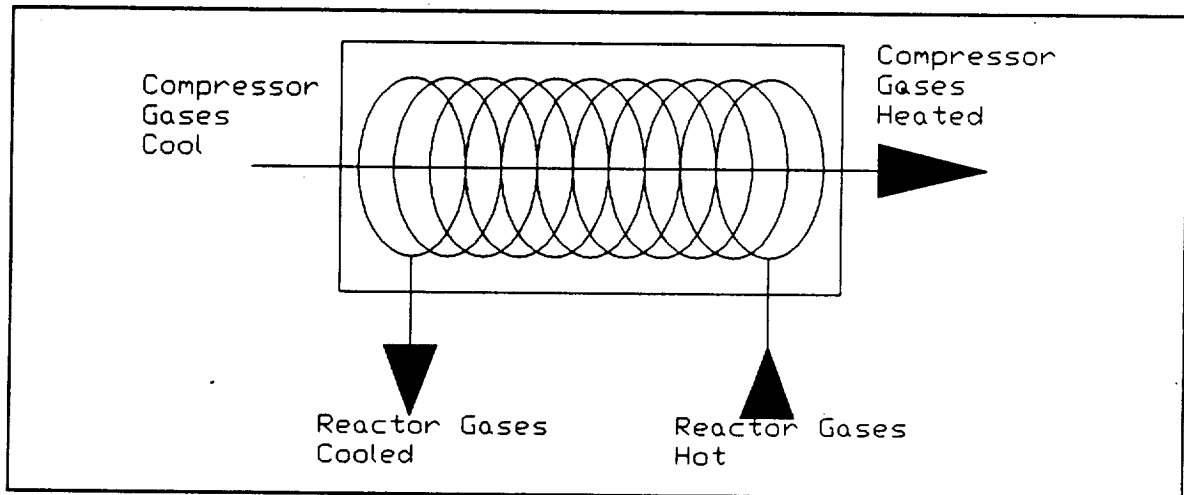


Figure 5.1-2. Regenerator (Preheater)

Conclusion

Any judgment on the validity of this model must wait until more of the heat exchanger's specifications are known. At that time comparison of data acquired from the actual heat exchanger in test and this simulation will be able to determine whether this model is valid or if more work needs to be done.

Areas in which this model might be improved would include: heat transfer from the heat exchanger to the ambient air if forced convection exists, variable liquid coolant temperatures if the reservoir is smaller than the one provided, modeling the pressure drop across the exchanger if the drop is significant when compared to the rest of the system.

ACCUMULATOR

Description

The carbon dioxide accumulator is a composite fiber/metal tank which can hold up to 90 minutes of continuous carbon dioxide flow. The tank is a cylinder with approximately 1 cu. ft of volume. Initially, 90 psia of carbon dioxide will be stored in the tank.

Details Of Operation

The tank is to be a buffer between the carbon dioxide removal system and the carbon dioxide reduction system. The carbon dioxide reduction system requires a constant flow of carbon dioxide from the tank, whereas the carbon dioxide removal system only provides carbon dioxide during the second and fourth quarters of its cycle. This causes pressure to build up during the second and fourth quarters and pressure to drop during the first and third quarters.

The temperature and composition of the carbon dioxide are not affected by the accumulator.

Assumptions

1. The air in the system can be treated as an ideal gas. Since the air is only compressed to a maximum 6.5 atmospheres, the ideal gas equation approximation will still be valid.
2. Temperature is constant.

3. The mass flow, m , is constant. This is assumed because the NASA literature states that a constant flow of carbon dioxide is needed for the carbon dioxide removal system.

Derivation Of Equations

The ideal gas equation states

$$PV = nRT. \quad (5.1-34)$$

Since the temperature and volume are assumed constant, the only parameters that vary are the pressure and the mass flow. Differentiation of Eq. (5.1-34) gives

$$\frac{dP}{dt} = \frac{R \cdot T}{V} \Delta t (m_1 - m_2), \quad (5.1-35)$$

where the following definitions are required:

$\frac{dP}{dt}$ - pressure change within the accumulator (kPa/second),

T - temperature of the gas (K),

R - universal gas constant (kJ/kmol·K),

m_1 - mass flow in (kg/s),

m_2 - mass flow out (kg/s),

$$P(\text{new}) = P(\text{old}) + \frac{dP}{dt} \cdot \Delta t,$$

$P(\text{new})$ - temperature at present time (kPa),

$P(\text{old})$ - temperature at present time minus Δt (kPa),

Δt - time increment (s).

FAN

Description

The blower is a centrifugal fan with backwardly curved blades. Air from the fan is discharged into a vane-less diffuser which slows the air flow. Further downstream, de-swirl vanes are used to slow air movement even more. The fan housing is corrosion resistant and leak proof.

Details Of Operation

The blower is used to move the air through the carbon dioxide removal cycle of the four bed molecular sieve. Motor driven centrifugal impellers are used to force the air through the system, however, this process adds velocity, swirling and heat to the process-air. A diffuser and de-swirl vanes downstream of the blades are used to change the velocity pressure and swirl energy into usable static pressure. This compression, as well as the heat given off by the motor cause a significant change in the temperature of the air. The composition and flow rate of the air do not change in the blower.

Assumptions

1. The process-air is an ideal gas. The compression of the air is not great enough to affect the results of the ideal gas equations.
2. The fan reaches steady state in a short time compared to the cycle time of the system. The test data received from NASA justifies this assumption.
3. The fan runs at constant speed.

Derivation of Equations

The transfer of heat from the motor to the process-air is represented by the equation

$$\dot{Q} = \dot{m} \cdot c_p \cdot (T_2 - T_1) . \quad (5.1-36)$$

Solving for T_2 gives

$$T_2 = T_1 + \frac{Q}{\dot{m} c_p},$$

where

T_2 - outlet air temperature (K) ,

T_1 - inlet air temperature (K) ,

\dot{Q} - fan power consumption (W) ,

\dot{m} - air mass flow rate (kg/s) ,

c_p - specific heat of air (J/kg·K) .

From NASA test data, the following values were determined:

fan flow rate = 22.3 cfm
fan outlet pressure = 1.8 to 2.1 psig
fan power consumption = 285 BTU/hr.

With the use of this data, T_2 can be written as

$$T_2 = T_1 + 263.33 \text{ K.} \quad (5.1-37)$$

Time Response Of The Fan

Since steady state operation was assumed, no time response characteristics were evaluated. Data from NASA does not indicate much of a time lag between start up and steady state conditions.

Conclusion

Care should be taken so that steady state is not assumed unless it is valid. A good deal of time this semester was spent clarifying exactly when steady state conditions are valid.

CARBON DIOXIDE PUMP

Description

The Carbon dioxide pump uses a motor driven rotary vane to force the carbon dioxide through the system. The rotor is mounted on a housing which is enclosed by two end plates.

Details of Operation

The rotor is eccentrically mounted with respect to the housing, so that when the rotor revolves the vanes vary in distance from the housing. At the start of the process, the vanes are at the closest point to the housing. As the process proceeds the vanes move away from the housing creating space which is filled from the suction of the pump. Once the distance between the vanes and the housing start to decrease, the carbon dioxide is force out the opposite valve port into the exhaust of the pump.

Assumptions

1. The carbon dioxide is an ideal gas. The carbon dioxide in the pump is under low compression, and is nearly pure.
2. The process is adiabatic.
3. The process is isentropic. This is a good assumption to start with, but efficiencies should included later.
4. The volumetric flow rate through the pump is constant. Even though not all of the CO₂ is removed on the high pressure side and returns to the low pressure side, this return mass is negligible compared to the mass entering the pump, so this assumption is valid.
5. The specific heat of the carbon dioxide is constant. The temperature range is small enough to make this assumption.

Derivation of Equations

The relationship between pressure and volume in a compression process can be given by the equation $pV^k = \text{constant}$ which is called a polytropic process. Combining this equation with ideal gas behavior, $pV = nRT$, the relationship $pV^k = \text{constant}$ for the pump can be derived.

The temperature and pressure on the intake side of the pump are known from taking

measurements on the outside of the adsorbent beds. The pressure head on the out side of the pump is controlled by the CO₂ accumulator tank. This pressure is measured and is at least 620 Kpa. The temperature of the exiting compressed CO₂ is then given by the equation

$$T_2 = T_1 \cdot \left(\frac{p_2}{p_1} \right)^{\frac{k-1}{k}}, \quad (5.1-38)$$

where

T_2 - gas exit temperature (K),

T_1 - gas inlet temperature (K),

p_2 - gas exit pressure (kPa),

p_1 - gas inlet pressure (kPa),

k - specific heat ratio.

Since the specific heats for CO₂ are taken as constants, their ratio is also a constant and given by this formula

$$k = \frac{C_p(T_{avg})}{C_v(T_{avg})}, \quad (5.1-39)$$

where

T_{avg} - average of T_1 and T_2 .

To calculate the power required to run the pump, it is first necessary to calculate a mass flow rate through the pump. The volume flow rate through the pump is measured and assumed to be constant. Measuring the temperature and pressure entering the pump, the specific volume of the CO₂ gas can be found and then the mass flow rate, dm/dt , is calculated by dividing the volume flow rate, dV/dt , by the specific volume, v .

The ideal gas power requirement for the pump is given by the formula

$$\frac{dW}{dt} = \frac{\frac{dm}{dt} \cdot R \cdot (T_2 - T_1)}{1 - k},$$

(5.1-40)

where

$\frac{dW}{dt}$ - isentropic pump power consumption (W),

$\frac{dm}{dt}$ - mass flow rate (kg/s),

R - ideal gas constant (kJ/kg·K),

T_2 - gas exit temperature (K),

T_1 - gas inlet temperature (K),

k - specific heat ratio.

Time Response of the Pump

All of the equations used to describe this CO₂ pump are from steady state analysis. The time for the pump to reach steady state is negligible compared to the amount of time that the pump runs at steady state operation.

Discussion of Results

The analysis of the CO₂ pump involved several simplifying assumptions that could be removed in future analyses. Pump efficiency should be looked into as rotary vane pumps are not too efficient. This would require more electrical energy to the pump motor. Also, future analyses might have some heat transfer to the CO₂ gas and also to the surroundings of the pump.

This steady state analysis of the CO₂ pump does give a good approximation of the

pump operation and can be useful in a simulation of the CO₂ removal subsystem.

Nominal values of properties for the pump are as follows:

$$T_1 = 300 \text{ K to } 450 \text{ K}$$

$$p_1 = 3.45 \text{ kPa}$$

$$p_2 = 620 \text{ Kpa}$$

$$\dot{m} = 0.333 \text{ kg/hr}$$

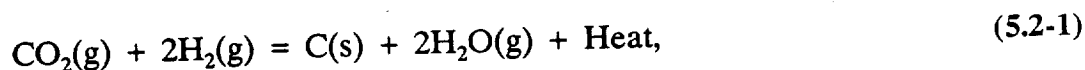
$$k = 1.27$$

5.2 CARBON DIOXIDE REDUCTION

BOSCH REDUCTION REACTOR

Overview

Carbon dioxide from the carbon dioxide removal subsystem and hydrogen from the oxygen generation subsystem react over an iron catalyst (steel wool) in the temperature range 800 K to 1000 K to produce solid carbon and water vapor according to the reaction



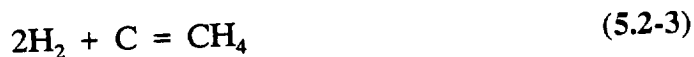
where the heat of reaction has the value

$$H_{\text{rxn}} = 99440 \text{ J/mole CO}_2.$$

Single pass efficiencies for this reaction are around 6%. Therefore a recycle loop is required for complete conversion. The recycle loop contains un-reacted CO_2 and H_2 , side products CO , CH_4 and N_2 . The N_2 is a contaminant gas that enters with the CO_2 . The remaining products in the recycle loop are formed by the secondary reactions



and



Detailed Description

The CO_2 enters from the CO_2 removal subsystem. It is mixed in the recycle loop and forced downstream by a two speed compressor. A slip stream is taken off and fed through a gas composition controller. The thermal conductivity of the slip stream is measured and then compared to a set point. The controller either meters in the appropriate amount of H_2 or vents the excess H_2 through a relief valve. This is done because it is necessary to have a volumetric ratio of 2:1 ($\text{H}_2:\text{CO}_2$) entering the reactor at all times. The gas mixture is preheated through a regenerative heat exchanger before entering the reactor. The reactor is generally operated isothermally at 922 K. This temperature is maintained by an electrical heater in the reactor. The mixture leaves the heat exchanger and flows through the reactor where the CO_2 and H_2 are converted to solid carbon and water vapor. Carbon is deposited on the iron catalyst. The un-reacted CO_2 and H_2 , the side products CO , CH_4 , N_2 , and water vapor all leave the reactor to exchange heat with the incoming gases in the

regenerative heat exchanger. The gas mixture then flows through the condenser/separator where the majority of the water vapor is condensed and removed. The remaining gas mixture returns to the compressor. Since the N_2 does not react, it causes a pressure build up in the recycle stream. Therefore, it is necessary to periodically bleed off a portion of the recycle stream through a back pressure regulator. When the reactor becomes full of carbon, it is necessary to switch over to a second reactor since the CO_2 reduction rate declines as carbon is deposited on the catalyst.

Discussion of Modeling the Reactor

A complete mathematical model of the reactor could not be derived because the necessary information was not provided in the available literature. As an alternative, a discussion of how a model can be derived if the necessary information is available will be provided below.

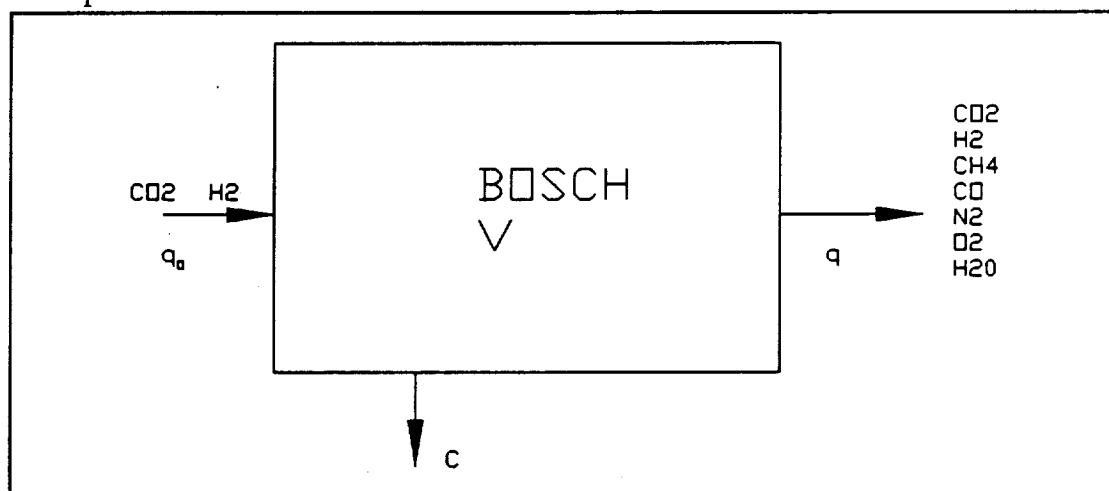


Figure 5.2-1. Mass Balance Diagram

The high recycle rate allows the reactor to be modeled as a continuously stirred tank reactor (CSTR). With this assumption, material balances can be made on any component in Figure 5.2-1 according to the general differential mass balance equation

$$V \cdot \left(\frac{\partial C_x}{\partial t} \right) = q_0 \cdot C_{x0} + q \cdot C_x + r_x \cdot W, \quad (5.2-4)$$

where the following definitions hold:

V = reactor volume (l),

q_0 - inlet volumetric flow rate (l/s) ,

q - outlet volumetric flow rate (l/s) ,

C_{x0} - inlet concentration of component x (mol/l) ,

C_x - outlet concentration of component x (mol/l) ,

r_x - rate of reaction (mol/s.kgcatalyst) ,

W - catalyst weight (kg) .

To solve this equation, it is necessary to know the rates of reaction for the main reaction and the side reactions. The inlet and outlet volumetric flow rates and inlet concentration of each component must also be known as a function of time. None of this information was provided in the literature. If these things were available, the material balance could easily be solved for isothermal conditions to give a transient description of the reactor.

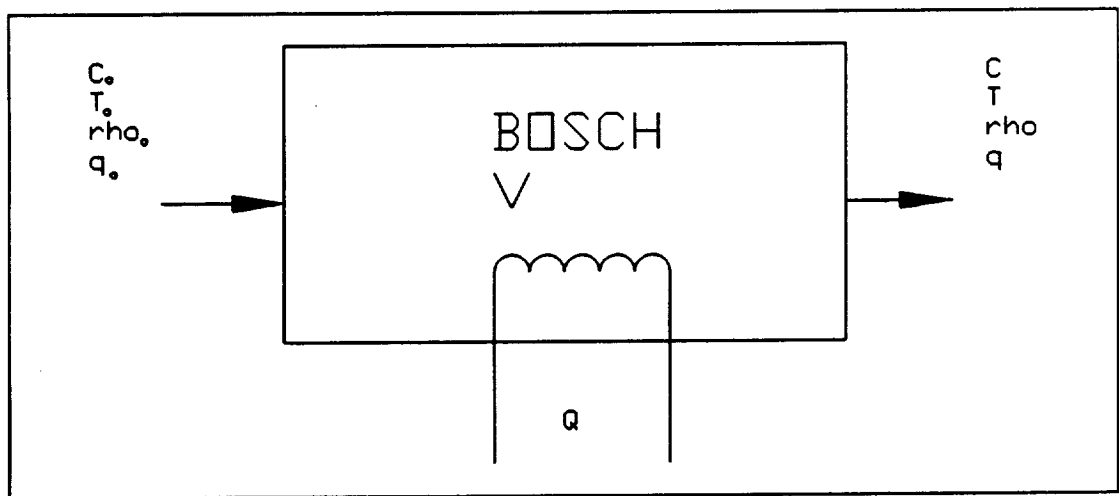


Figure 5.2-2. Schematic Diagram for Energy Balance

If the reactor is not operating isothermally, then an energy balance for the reactor must be written since the mass balance will now be a function of temperature. An energy balance for the reactor shown in Figure 5.2-2 can be written in the form

$$\rho \cdot Q \cdot C_p \cdot \frac{\partial T}{\partial t} = \rho_0 \cdot Q_0 \cdot C_{p0} \cdot (T_0 - T_{ref}) + \rho \cdot Q \cdot C_p \cdot (T - T_{ref}) + r_x \cdot (-H_{rxn}) \cdot W + Q \quad (5.2-5)$$

with the following definitions:

ρ_0 - density of entering gas mixture (g/l) ,

C_{p0} - heat capacity of entering gas mixture (J/g·K) ,

ρ - density of exiting gas mixture (J/g·K) ,

c_p - heat capacity of exiting gas mixture (J/g·K) ,

T - outlet temperature (K) ,

T_0 - inlet temperature (K) ,

T_{ref} - reference temperature (K) ,

H_{rxn} - heat of reaction (J/mol) ,

Q - energy input heater (W) .

This balance assumes that there is no heat loss due to radiation or convection since the reactor is well insulated. Once again, this equation cannot be solved since the rate of reaction is unknown. The rate of reaction contains the temperature dependence of the reaction. If this was available, the energy balance and the mass balance can be solved simultaneously to give a transient description of the temperature and composition in the reactor.

Conclusions

The major problem with modeling the Bosch reactor is that the rate equation is unknown. Without the rate equation, the mass and energy balances cannot be solved.

In an attempt to derive a rate equation from the available literature, the graph on p. 28 of "Performance Characterization of a Bosch CO₂ Reduction Subsystem"(5.2-1) was used to calculate the rate using the following equation for a CSTR.

$$r = \frac{(-X \cdot F_{CO_2})}{W}, \quad (5.2-6)$$

where the symbols are defined as

r - rate of reaction (kgCO₂/min·kgcatalyst) ,

F_{CO_2} - CO₂ reduction rate (kg/min) ,

W - weight of catalyst (kg) ,

X - conversion (equal to unity for CO₂) .

The rate was plotted versus time. It was hoped that this data would exhibit some sort of behavior that would allow it to be fitted to a typical rate equation model. It was hoped that the rate would be an exponential decay. Unfortunately, the data did not decay exponentially. The data was essentially linear. The slope and intercept of the line were calculated. This equation was of no use for several reasons. First, the data was taken at a temperature of 922K. It would not be valid to extend the equation over a range of temperatures in an energy balance. Second, the data was taken at steady state conditions. It would not be valid to use this equation in mass and energy balances to determine the transient responses. Third, the equation was a linear function of time. This equation was not a characteristic equation for the rate. It is expected that the rate is some function of concentration, temperature, and time. Therefore, this rate equation was not used. It is possible that a rate equation has not yet been determined for this reaction.

In addition to the rate equation, the time dependence of the inlet flow rate and concentrations of CO₂ and H₂ must be known in order to solve the mass balance. At this time, it is not known how they vary. The flow rate and concentrations depend on many things, and they are continuously changing with every pass. It may be a good idea to look into this after more research has been done.

Once the rate equation and the time dependence of the inlet concentrations and flow rate of CO_2 and H_2 are known, the reactor can be easily modeled.

REGENERATOR (HEAT EXCHANGER)

The regenerator preheats the H_2 and CO_2 gases flowing into the Bosch reactor so that efficiency of the reaction can be increased. This process also reduces the power requirements of the reactor i.e. the resistive heater in the reactor uses less energy.

Details of Operation

The regenerator transfers the heat from CO_2 , H_2O , CO , and CH_4 gases produced during the Bosch reaction to CO_2 and H_2 (with traces of CO and CH_4 after the first few cycles) gases coming out of the compressor so that the efficiency of the Bosch reaction will be increased. Most heat exchangers are made of stainless steel so it is safe to assume that the regenerator is made of stainless steel. Because the regenerator is used for the transfer of heat between two gases, as are compact or cross flow heat exchangers, it is logical to assume that the regenerator must be one of these two types of heat exchangers. The compact and cross flow heat exchangers are unmixed and are used for gases because of the larger surface area for the heat transfer to take place.

Assumptions

The following list of assumptions were made to simplify the modeling of the regenerator. The assumptions are:

- 1) No heat transfer to surroundings
- 2) Constant specific heats for the materials over the temperatures of interest
- 3) Kinetic and potential energy effects are negligible
- 4) The gas mixes are uniformly mixed
- 5) The gases are ideal
- 6) The mass flow rates in and out are the same
- 7) The pressure drop across the regenerator is negligible
- 8) No transfer of heat to the surroundings

Differential Equations from Fundamental Principles

The differential equations use the relationship between the heat transfer, area, change in temperature and the heat transfer coefficient based on the conservation of energy and effectiveness-NTU. The heat transfer rate is given by

$$q = U \cdot A \cdot (T_2 - T_1) \quad (5.2-7)$$

with the definitions

q - heat transfer rate (Watts) ,

T_2 - exiting temperature (K) ,

T_1 - entering temperature (K) ,

A - surface area (m^2) ,

U - overall heat transfer coefficient ($W/m^2 \cdot K$) .

one can write

$$U \cdot A = E \cdot \dot{m} \cdot c_p, \quad (5.2-8)$$

where

E - effectiveness of the heat exchanger
(dimensionless) .

\dot{m} - mass flow rate of material (kg/s) ,

c_p - specific heat of the material ($J/kg \cdot K$) .

For the regenerator there are two heats transfer rates, q_{1HX} and q_{2HX} which are given by (See Figure 5.2-3)

$$q_{1HX}(t) = (T_c(t) - T_{HX}(t)) \cdot U \cdot A_1 \quad (5.2-9)$$

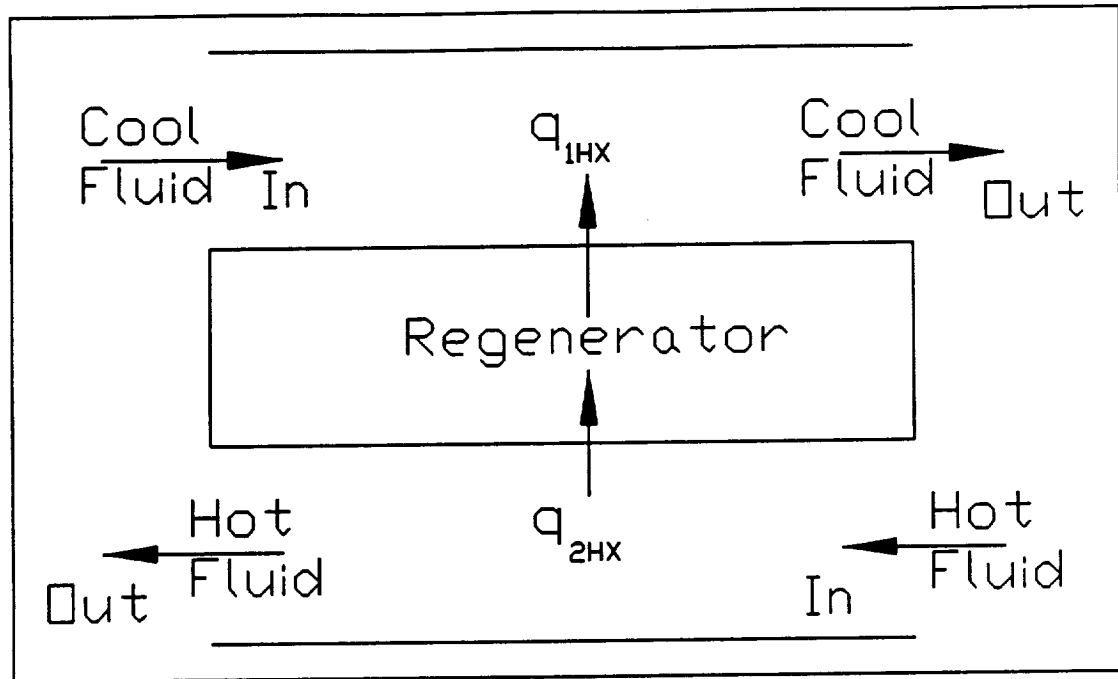


Figure 5.2-3. Regenerator Heat Transfer Diagram

and

$$q_{2HX}(t) = (T_h(t) - THX(t)) \cdot U \cdot A_2, \quad (5.2-10)$$

where the following definitions are required:

q_{1HX} - heat transfer rate to the cold gases (W),

q_{2HX} - heat transfer rate from the hot gases (W),

THX - temperature of the regenerator (K),

T_c - temperature of the entering cold gases (K),

T_h - temperature of the entering hot gases (K),

A_1 - area contacting the cold gases (m^2),

A_2 - area contacting the hot gases (m^2),

U - overall heat transfer coefficient for the regenerator ($W/m^2 \cdot K$).

If the regenerator starts out at room temperature (300 K), the regenerator will transfer less heat from the hot gases to the cooler gases because the regenerator will retain some of the heat. This can be expressed as the change in heat transferred to the gases and the amount stored in the heat exchanger starting at time equal to zero. This is expressed as

$$\frac{dTHX(t)}{dt} = \frac{q1HX(t) + q2HX(t)}{M_{HX} \cdot C_{PHX}}, \quad (5.2-11)$$

where

M_{HX} - mass of the regenerator (kg),

$dTHX$ - temperature change of the regenerator (K),

dt - change in time (s).

By substituting in for the $q1HX$ and $q2HX$, Equation (5.2-11) can be written as

$$\frac{dTHX(t)}{dt} = \frac{U \cdot (A_1 \cdot (T_c(t) - THX(t)) + A_2 \cdot (T_h(t) - THX(t)))}{M_{HX} \cdot C_{PHX}}. \quad (5.2-12)$$

If $A_1 = A_2$, then

$$\frac{dTHX(t)}{dt} = \frac{U \cdot A \cdot (T_c(t) + T_h(t) - 2 \cdot THX(t))}{M_{HX} \cdot C_{PHX}} \quad (5.2-13)$$

The temperature of the gas as it leaves the regenerator will be different than when it entered. This property is expressed as

$$T_{c2}(t) - T_{c1}(t) = \frac{q1HX(t)}{\dot{m}_c \cdot C_{pc}} \quad (5.2-14)$$

with the definitions

\dot{m}_c - mass flow rate of cold gases (kg/s) ,

\dot{m}_h - mass flow rate of hot gases (kg/s) ,

c_{pc} - specific heat of cold gases (J/kg·K) ,

c_{ph} - specific heat of the hot gases (J/kg·K) ,

T_{c2} - temperature of the exiting cold gases (K) ,

T_{c1} - temperature of the entering cold gases (K) ,

T_{h2} - temperature of the exiting hot gases (K) ,

T_{h1} - temperature of the entering hot gases (K) .

When the regenerator reaches steady state, the magnitude of the rate of heat transfer to and from the regenerator will be equal. There is a sign difference that indicates the direction of the transfer. ie. $q_{2HX} = -q_{1HX}$

Transfer Function

The transfer function is derived from the differential Equation (5.2-13) derived in the above section as

$$\frac{dTHX(t)}{dt} = \frac{U \cdot A \cdot (T_{c1}(t) + T_{h1}(t) - 2 \cdot THX(t))}{M_{HX} \cdot C_{pHX}} \quad (5.2-15)$$

The Laplace transform yields

$$s \mathcal{L}(THX(t)) - THX(0) + \frac{2 \cdot U \cdot A}{M_{HX} \cdot C_{pHX}} \mathcal{L}(THX(t)) = \frac{U \cdot A \cdot [\mathcal{L}(T_{c1}(t)) + \mathcal{L}(T_{h1}(t))]}{M_{HX} \cdot C_{pHX}}$$

If the initial condition ,THX(0), is equal to zero then factor out $L\{THX(t)\}$. The resulting equation is:

$$\mathcal{L}(THX(t)) = \frac{U \cdot A \cdot [\mathcal{L}(T_{c1}(t)) + \mathcal{L}(T_{h1}(t))]}{s \cdot M_{HX} + 2 \cdot U \cdot A} \quad (5.2-16)$$

The inverse Laplace transform cannot be derived until the equations for $T_{c2}(t)$ and $T_{h1}(t)$ are known. The temperature $T_{c1}(t)$ is the same as the output temperature of the compressor and $T_{h1}(t)$ is the same as the output temperature of the Bosch reactor.

Time Response

The time response equation cannot be developed.

Discussion of Results

The regenerator works as a preheater that transfers the energy stored in the gases exiting the Bosch reactor to the gases coming from the compressor. The regenerator will not be at a working temperature instantaneously but it will start out at room temperature. The equations derived above describe how the regenerator starts from its cool state and warms to its operating temperature. The rate at which the warming occurs is dependent on the physical characteristics of the heat exchanger.

Useful Information for new students

1. The main tool that is not fully utilized by students is seeking help from faculty.
2. The AR system is large and it is easy to become overwhelmed by its complexity. It is a good idea to first understand the other sub systems.
3. EASY5 models were used to model the heat exchanger. The key to modeling any component is to understand the characteristics of component at steady state and then begin working on the transient model.
4. An important concept for understanding this model is to realize that the heat exchanger has thermal capacitance.

5.3 OXYGEN GENERATION

The Oxygen Generation Assembly has two main components to model, the water tank and the electrolysis module. The valves in the system were omitted at this time since they are either completely opened or closed. A sketch of the system along with the notations used is shown in Figure 5.3-1.

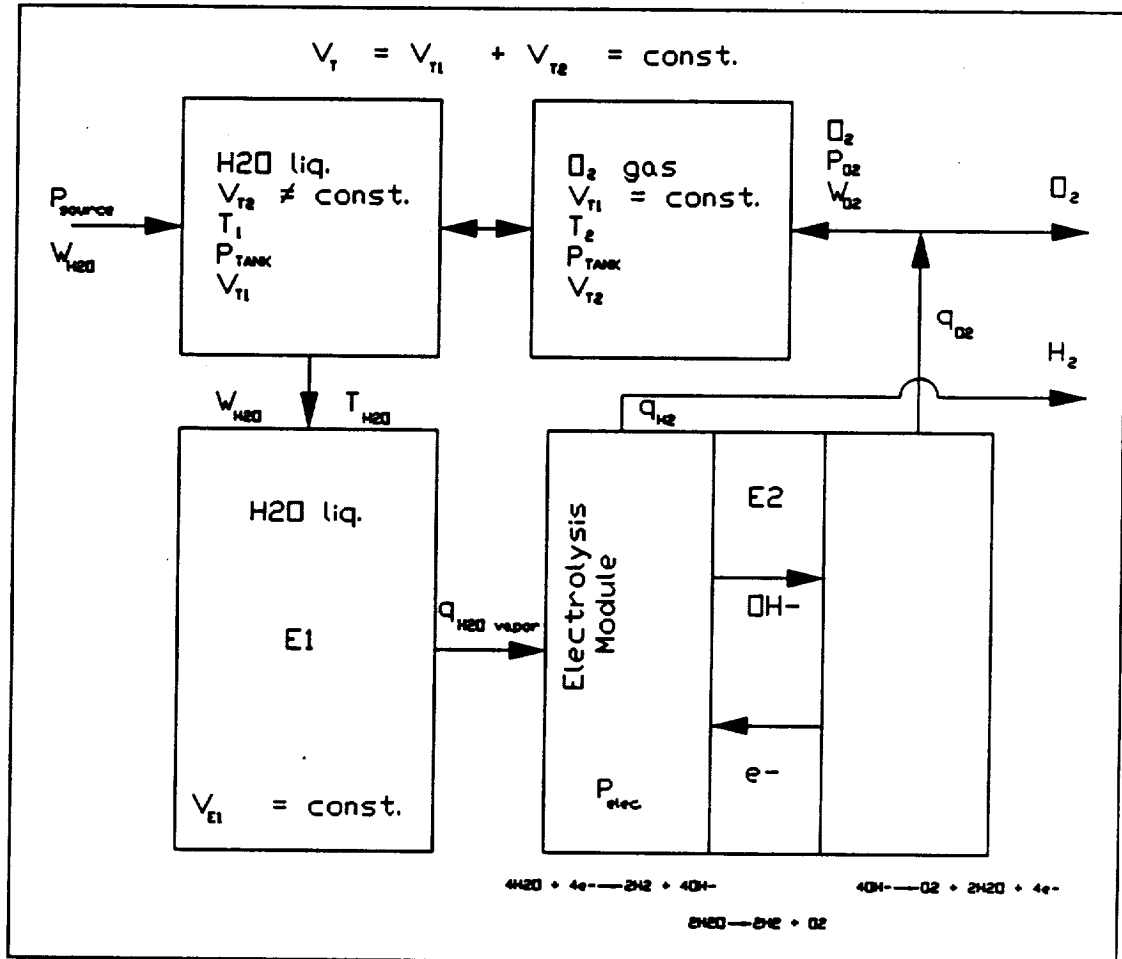


Figure 5.3-1. Oxygen Generation Assembly System Notation

WATER TANK

Details Of Operation

The water tank has two modes of operation, the fill mode and the drain mode. During the fill mode, the water tank is isolated from the electrolysis module, and the oxygen on the one side of the bellow is released to the cabin causing a reduced pressure in the oxygen side of the tank. A schematic of the water tank is shown in

Figure 5.3-2. This reduced pressure causes the tank to fill with water from an outside water source. In the drain mode, the feed water cavity in the electrolysis module is continuously filled from the water tank which is kept under pressure by a portion of the oxygen product gas. The water tank is in the drain mode for three hours, and then takes four to five minutes to refill.

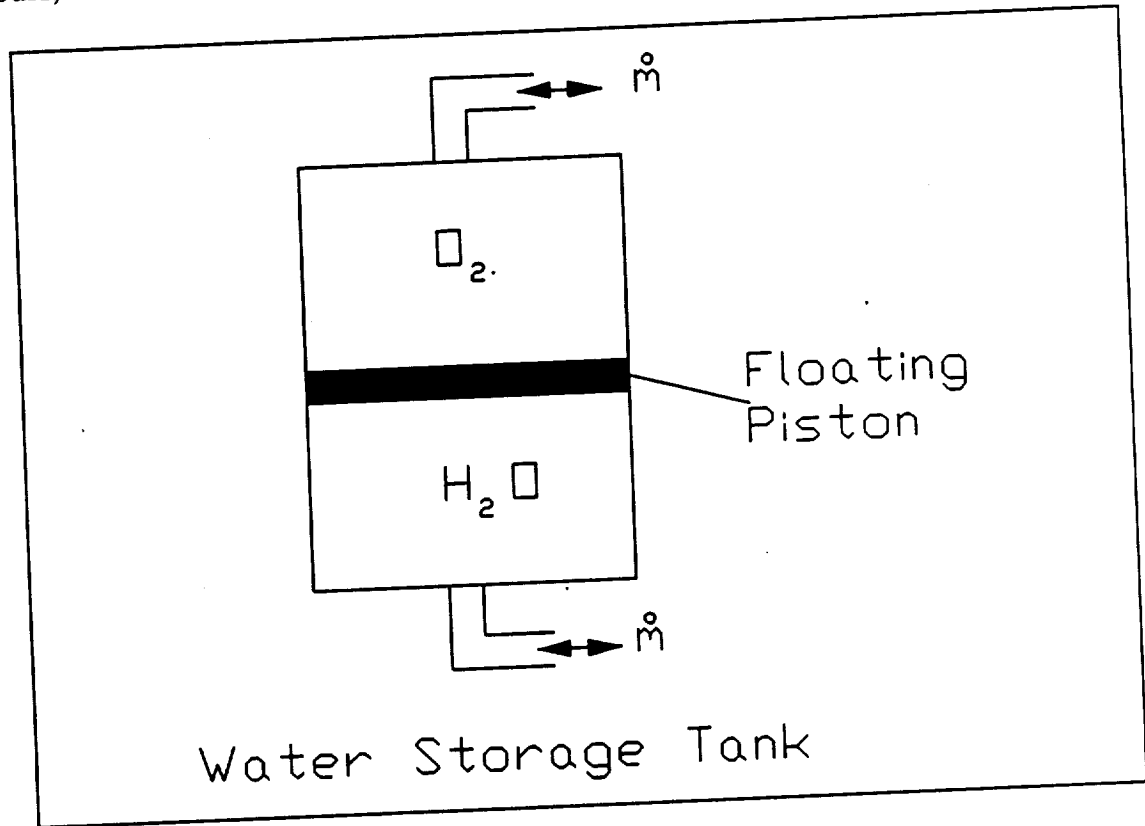


Figure 5.3-2. Water Tank Schematic

The mathematical modeling for the water tank can be done by modeling it as two dependent tanks, the water portion, and the oxygen portion.

Assumptions

1. Water has constant physical properties.
2. Oxygen has constant heat capacity.
3. The water flow into the storage tank can be considered as turbulent since it flows in over a four to five minute period.
4. The water flow out of the storage tank can be considered as laminar since it flows out over a three hour period.

5. The oxygen flow into and out of the storage tank can be considered as turbulent.
6. Oxygen follows the ideal gas law.

Water Portion Of Water Tank

When modeling the water portion of the water tank, the dependent variables of interest are the change in the volume and temperature, and the inlet and outlet water flows.

A material balance can be written to relate the change in volume of the tank with respect to time. This material balance can be written as

Rate Of Mass Accumulation = [Rate Of Mass]_{in} - [Rate of Mass]_{out}.

Symbolically this becomes

$$\frac{\rho_{H_2O} dV_{T1}}{dt} = W_{H_2O, in} - W_{H_2O, out} \quad (5.3-1)$$

where the following definitions are required:

V_{T1} = Volume of water compartment of storage tank (m³),
 $w_{H_2O, in}$ = Mass flow rate of water in (Kg/sec),
 $w_{H_2O, out}$ = Mass flow rate of water out (Kg/sec),
 ρ_{H_2O} = Density of water (kg/m³).

During the tank fill mode, the $w_{H_2O, out}$ term in Equation 5.3-1, is equal to zero, and in the drain mode, the $w_{H_2O, in}$ term is equal to zero.

Since the tank takes four to five minutes to fill, it is probably a good assumption that the water flowing into the tank is in turbulent flow. In deriving an equation for the turbulent flow of water through a tube, a good starting point is the Blassius Formula for friction factors. (5.3-1) The Blassius Formula is as follows:

$$f = \frac{0.0791}{Re^{1/4}} \text{ for } 2.1 \times 10^3 < Re < 10^5, \quad (5.3-2)$$

where

Re = the Reynolds number given by $Re = D \langle v \rangle \rho_{H_2O} / \mu_{H_2O}$,
 D = the tube diameter (m),
 $\langle v \rangle$ = the average velocity of the water (m/sec),
 μ_{H_2O} = the viscosity of water (Kg/m sec).

When the definition for Reynolds number is substituted into the Blassius Formula, Equation 5.3-2 becomes

$$f = \frac{0.0791}{(D \langle v \rangle P_{H2O} / u_{H2O})^{1/4}} \quad (5.3-3)$$

The friction factor can also be written as (5.3-1).

$$f = \frac{D(P_{source} - P_{v1})}{4L(1/2 P_{H2O} \langle v \rangle^2)}, \quad (5.3-4)$$

where

P_{source} = the pressure of the external water source
(N/m²),

P_{v1} = the pressure in the water side of the tank (N/m²),

L = the tube length (m).

Setting Equation 5.3-3 and Equation 5.3-4 equal to each other gives

$$f = \frac{0.0791}{(D \langle v \rangle P_{H2O} / u_{H2O})^{1/4}} = \frac{D(P_{source} - P_{v1})}{L(1/2 P_{H2O} \langle v \rangle^2)} \quad (5.3-5)$$

Multiplying each side by the tube cross sectional area ($A = \pi r^2$) and then rearranging gives

$$P_{H2O} \langle v \rangle A = \frac{(D^{5/4} P_{H2O} (P_{source} - P_{v1}))^{4/7} A}{((0.0791)(2) L u_{H2O}^{1/4})^{4/7}} \quad (5.3-6)$$

Equation 5.3-6 can then be substituted into Equation 5.3-1 since

$$W_{H2O, in} = P_{H2O} \langle v \rangle A. \quad (5.3-7)$$

Now that we have derived an equation for the change in volume of the water tank during the fill mode with respect to time, we need an equation that models volume change when the water is flowing out of the tank. The water in the tank flows out over a period of three hours, so we can assume that this flow would be laminar. The laminar flow of a fluid through a tube is given by the Hagen-Poiseuille law (5.3-1). The Hagen-Poiseuille law is given by

$$Q = \frac{\pi (P_{v1} - P_{elec}) r^4}{8 u_{H2O} L}, \quad (5.3-8)$$

where P_{elec} = the pressure in the electrolysis module.

Equation 5.3-8 can be changed into mass flow rate by multiplying by p_{H_2O} to obtain

$$W_{H_2O, out} = \frac{\pi (P_{v1} - P_{elec}) r^4 P_{H_2O}}{8 u_{H_2O} L} \quad (5.3-9)$$

Equation 5.3-9 can then be substituted in to Equation 5.3-1, to give the volume change of the water portion of the water tank during the drain mode.

Now that we have equations that model the change in volume of the tank during the fill and drain modes, an equation needs to be derived to relate the change in temperature of the water with respect to time. This can be done by writing an energy balance on the system. The energy balance for the water portion of the water tank is give by

$$[\text{Rate of Energy}] = [\text{Rate of Energy}]_{in} - [\text{Rate of Energy}]_{out} - [\text{Net Rate of Heat Loss to Surroundings}].$$

Symbolically this becomes

$$P_{H_2O} C_{P_{H_2O}} \frac{d(V_{T1} (T_{H_2O} - T_{ref}))}{dt} = W_{H_2O, in} C_{P_{H_2O}} (T_{H_2O, in} - T_{ref}) - W_{H_2O, out} C_{P_{H_2O}} (T_{H_2O} - T_{ref}) - Q_{cond, H_2O} - Q_{rad, H_2O} \quad (5.3-10)$$

where the following definitions are required:

- $C_{P_{H_2O}}$ = heat capacity of Oxygen. (KJ/Kg K)
- $T_{H_2O, in}$ = temperature of oxygen into the compartment (K).
- T_{H_2O} = temperature of oxygen out of the compartment (K).
- Q_{cond, H_2O} = heat loss by conduction (KJ/sec).
- Q_{rad, H_2O} = heat loss by radiation (KJ/sec).

The in and out mass flow rate terms are given by Equations 5.3-7 and 9 respectively, and the heat loss by conduction through the tank walls, bottom, and bellow can be written as (5.3-1)

Here the needed definitions are

- r_o = inside radius of the tank (m),
- r_1 = outside radius of the tank (m),
- r_{bot} = thickness of the bottom of the tank (m),

$$\begin{aligned}
Q_{\text{cond, H2O}} = & \frac{2V_{T1}}{r_0} \left[\frac{1}{h_{H2O}} + \frac{1nr_1/r_0}{K_T} + \frac{1}{r_1 h_{\text{surr}}} \right]^{-1} (T_{H2O} - T_{\text{surr}}) \\
& + 2\pi r_0^2 \left[\frac{1}{h_{H2O}} + \frac{r_{\text{bot}}}{K_T} + \frac{1}{h_{\text{surr}}} \right]^{-1} (T_{H2O} - T_{\text{surr}}) \\
& + 2\pi r_0^2 \left[\frac{1}{h_{H2O}} + \frac{r_{\text{pist}}}{K_T} + \frac{1}{h_{O2}} \right]^{-1} (T_{H2O} - T_{O2}) .
\end{aligned} \quad (5.3-11)$$

r_{pist} = thickness of the piston in the tank (m),
 T_{O2} = temperature of oxygen in the tank (K),
 T_{surr} = temperature of surroundings (K),
 T_{H2O} = temperature of water in the tank (K),
 h_{O2} = heat transfer coefficient of oxygen (Kg/sec³ K),
 h_{H2O} = heat transfer coefficient of water (Kg/sec³ K),
 h_{surr} = heat transfer coefficient of surroundings (Kg/sec³ K),
 K_T = thermal conductivity of the tank (Kg m/sec³ K).

The heat loss due to radiation from the tank can be written as (5.3-1)

$$Q_{\text{rad, H2O}} = \frac{2V_{T1}\sigma(e_t T_{H2O}^4 - a_T T_{\text{surr}}^4)}{r_1}, \quad (5.3-12)$$

where

σ = Stefan-Boltzmann constant = 5.6693×10^{-11} (KJ/sec m² K⁴),
 e_T = the emissivity of the tank,
 a_T = the absorptivity of the tank.

The absorptivity can be estimated as the value of the emissivity.

The heat loss by radiation can be neglected since the tank is contained inside the space station and is not exposed to the cold temperatures of space.

The left hand side of Equation 5.3-10 can be expanded to the form,

$$C_{P_{H2O}} P_{H2O} (T_{H2O} - T_{\text{ref}}) \frac{dV_{T1}}{dt} + C_{P_{H2O}} P_{H2O} V_{T1} \frac{dT}{dt} \quad (5.3-13)$$

where p_{H_2O} & V_{T1}/dt term is given by Equation 5.3-1. When solved for dT/dt , Equation 5.3-10 relates the change in temperature of the water in the tank with time. This term will be small if the temperature of the water and the surroundings are about the same, and therefore the only dependent variables of interest in the water portion of the tank would be the change in the water compartment volume with respect to time, and the water flow rates.

Oxygen Portion Of Water Tank

When modeling the oxygen portion of the water tank, the dependent variables that are of interest are the mass flow rate of oxygen in and out of the compartment, the temperature in the compartment, the pressure in the compartment, and the volume of the compartment. These variables can all be related by integrating the ideal gas law with respect to time in the form

$$\frac{P_{O_2} dV_{T2}}{dt} + \frac{V_{T2} dP_{O_2}}{dt} = \frac{RT_{O_2} dn_{O_2}}{dt} + \frac{n_{O_2} R dT_{O_2}}{dt} \quad (5.3-14)$$

The dV_{T2}/dt term can be replaced by $-dV_{T1}/dt$ since

$$V_{\text{tank}} = V_{T1} + V_{T2} \quad (5.3-15)$$

Integrating with respect to time gives

$$\frac{dV_{\text{tank}}}{dt} = 0 = -\frac{dV_{T1}}{dt} + \frac{dV_{T2}}{dt} \quad (5.3-16)$$

The dn_{O_2}/dt term can be determined by making a mole balance on the oxygen compartment. The mole balance for the oxygen compartment of the water tank is given by

$$[\text{Rate Of Moles}] = [\text{Rate Of Moles}] - [\text{Rate of Moles}]$$

which is written symbolically as

$$\frac{dn_{O_2}}{dt} = (W_{O_2, \text{in}} - W_{O_2, \text{out}}) (1/M) \quad (5.3-17)$$

where

- n_{O_2} = moles of oxygen,
- $W_{O_2, \text{in}}$ = mass flow rate of oxygen in (Kg/sec),
- $W_{O_2, \text{out}}$ = mass flow rate of oxygen out (Kg/sec),
- M = molecular weight of oxygen (32).

The mass flow rates in and out of the oxygen portion could be considered turbulent. By editing the notation of Equation 5.3-6, it can be used to represent these flow rates, and can be written as

$$W_{O_2, in} = \frac{(D^{5/4} P_{O_2} (P_{O_2, elec} - P_{O_2, tank}))^{4/5} A}{((0.0791) (2) L u_{O_2}^{1/4})^{4/7}} \quad (5.3-18)$$

and

$$W_{O_2, out} = \frac{(D^{5/4} P_{O_2} (P_{O_2, tank} - P_{O_2, cabin}))^{4/5} A}{((0.0791) (2) L u_{O_2}^{1/4})^{4/7}}, \quad (5.3-19)$$

where

P_{O_2} = the density of oxygen at the given pressure
(Kg/m³),

$P_{O_2, elec}$ = pressure in the electrolysis module (N/m²),

$P_{O_2, tank}$ = pressure in the oxygen side of tank (N/m²),

$P_{O_2, cabin}$ = pressure in the cabin (1.01325x10⁵ N/m²),

u_{O_2} = the viscosity of oxygen (Kg/m sec).

The dT_{O_2}/dt term in Equation 5.3-14 can be found by making an energy balance on the system. The energy balance for the oxygen compartment of the water tank is give by

$$\begin{aligned} P_{O_2} C P_{O_2} \frac{dV_{T_2} (T_{O_2} - T_{ref})}{dt} - W_{O_2, in} C P_{O_2} (T_{O_2, in} - T_{ref}) \\ - W_{O_2, out} C P_{O_2} (T_{O_2} - T_{ref}) \\ - Q_{cond, O_2} - Q_{rad, O_2} \end{aligned} \quad (5.3-20)$$

The following definitions are required:

Cp_{O_2} = heat capacity of Oxygen (KJ/Kg K),

$T_{O_2, in}$ = temperature of oxygen into the compartment (K),

T_{O_2} = temperature of oxygen out of the compartment (K),

Q_{cond, O_2} = heat loss by conduction (KJ/sec),

Q_{rad, O_2} = heat loss by radiation (KJ/sec).

The $w_{O_2, in}$ and $w_{O_2, out}$ terms can be expressed by Equations 5.3-18 and 5.3-19. The heat loss by conduction through the tank walls, top, and piston can be written as (5.3-1)

where r_{top} = thickness of the top of the tank (m).

$$\begin{aligned}
& \frac{2V_{T2}}{r_0} + \left[\frac{1}{r_0 h_{02}} + \frac{1}{K_T} \frac{1}{r_1} + \frac{1}{r_1 h_{surr}} \right]^{-1} (T_{02} - T_{surr}) \\
& + 2\pi r_0^2 \left[\frac{1}{h_{02}} + \frac{r_{top}}{K_T} + \frac{1}{h_{surr}} \right]^{-1} (T_{02} - T_{surr}) \\
& + 2\pi r_0^2 \left[\frac{1}{h_{02}} + \frac{r_{pist}}{K_T} + \frac{1}{h_{H2O}} \right]^{-1} (T_{02} - T_{H2O}) ,
\end{aligned} \tag{5.3-21}$$

The heat loss due to radiation from the tank can again be written as (5.3-1)

$$Q_{rad} = \frac{2V_{T2}}{r_1} \sigma (e_t T_{02}^4 - a_T T_{surr}^4) \tag{5.3-22}$$

The heat loss by radiation can again be neglected since the tank is contained inside the space station and is not exposed to the cold temperatures of space.

The left hand side of Equation 5.3-20 can be expanded in the form

$$C_{pO_2} P_{O_2} (T_{O_2} - T_{ref}) dV_{T2}/dt + C_{pO_2} V_{T2} P_{O_2} dT_{O_2}/dt.$$

Noting that

$$P_{O_2} dV_{T2}/dt = dn_{O_2}/dt,$$

the left hand side of Equation 5.3-20 can be written as

$$W_{O_2, in} - W_{O_2, out} + C_{pO_2} V_{T2} P_{O_2} dT_{O_2}/dt. \tag{5.3-23}$$

We now have equations for dV_{T2}/dt , dn_{O_2}/dt , and dT_{O_2}/dt and they can be substituted into Equation 5.3-14 to give an equation for dP_{O_2}/dt . At any instant in time we know the pressure, temperature and moles of oxygen in the oxygen compartment of the water tank. We can also find the volume of the oxygen compartment. As stated before, the temperature term of this system could be considered constant if the temperature of the surroundings is approximately the same as the oxygen in the tank.

ELECTROLYSIS MODULE

Assumptions

1. Water has constant physical properties.
2. Water is an incompressible fluid.
3. The heat capacities of the gases are constant.
4. There is no accumulation of gases in the electrolysis module.
5. "The non-electrolytic 'parasitic' energy used by the electrolyzer per kilogram of water converted to gas" is negligible (5.3-2).
6. The amount of water vapor leaving in the product gases is negligible.

The electrolysis module will be modeled as a single cell for now. It can be modeled by dividing it up into the feed water compartment and the electrolysis compartment.

The dependent variables of interest in the feed water compartment are the inlet and outlet flow rates, and the change in temperature with respect to time. To determine the inlet and outlet flow rates, a material balance on the water compartment can be written as

$$P_{H_2O} \frac{dV_{E1}}{dt} = W_{H_2O, in} - W_{H_2O, out} \quad (5.3-24)$$

where the following definitions are used:

- V_{E1} = volume of water compartment in electrolysis module (m^3).
- $W_{H_2O, in}$ = mass flow rate of water in (Kg/sec).
- $W_{H_2O, out}$ = mass flow rate of water out (Kg/sec).
- P_{H_2O} = density of water (kg/m^3).

Since the volume of the water compartment in the electrolysis module is constant, and water is an incompressible fluid, Equation 5.3-24 can be written as

$$W_{H_2O, in} = W_{H_2O, out} \quad (5.3-25)$$

Since the flow into the water compartment is laminar, we get

$$W_{H_2O, in} = \frac{\pi (P_{tank} - P_{elec}) r^4 \rho_{H_2O}}{8 u_{H_2O} L} \quad (5.3-26)$$

from Equation 5.3-9. Although it is a vapor rate, the rate of water out could be modeled by the same equation. The flow rate out could also be estimated by deriving an expression for the diffusion of a vapor through a porous membrane. Since very little is known about the membrane, Equation 5.3-26 would give a better representation.

The energy balance for the water compartment would be similar to those for the water tank except for a water vaporization term. Such an energy balance would be written as follows:

$$\begin{aligned} C_{P_{H_2O}} V_{E1} \rho_{H_2O} \frac{dT_{H_2O}}{dt} - W_{H_2O, in} C_{P_{H_2O}} (T_{H_2O, in} - T_{ref}) \\ - W_{H_2O, out} C_{P_{H_2O}} (T_{H_2O} - T_{ref}) \\ - Q_{cond, E1} - Q_{rad, E1} \\ + (-h) W_{H_2O, out} \end{aligned} \quad (5.3-27)$$

Here the following definitions are used:

- $T_{H_2O, in}$ = temperature of water into the compartment (K).
- T_{H_2O} = temperature of water out of the compartment (K).
- $Q_{cond, E1}$ = heat loss by conduction (KJ/sec).
- $Q_{rad, E1}$ = heat loss by radiation (KJ/sec).
- $-h$ = heat of vaporization of water (KJ/Kg).

The $w_{H_2O, in}$ and $w_{H_2O, out}$ terms can be replaced by Equation 5.3-26, and the heat loss by conduction through the tank walls can be expressed as (5.3-1)

$$A_{E1} \left[\frac{1}{r_{E0} h_{H_2O}} + \frac{1}{K_T} \ln \frac{r_{E1}}{r_{E0}} + \frac{1}{r_{E1} h_{surr}} \right]^{-1} (T_{H_2O} - T_{surr}) \quad (5.3-28)$$

with

- r_{E0} = inside radius of the tank (m).
- r_{E1} = outside radius of the tank (m).
- A_{E1} = surface area of the water compartment, excluding the side with the membrane (m²).

The heat loss due to radiation from the tank can be written as (5.3-1) with e_{E1} = the emissivity of the compartment.

$$Q_{rad, E1} = A_{E1} \sigma (e_{E1} T_{H2O}^4 - a_{E1} T_{surr}^4), \quad (5.3-29)$$

a_{E1} = the absorptivity of the compartment.

The temperature in the feed water compartment at any instant of time is now known. The inlet and outlet flow rates can also be calculated.

In modeling the electrolysis module, the dependent variables of interest are the rate of production of hydrogen and oxygen, and the change in temperature in the module. To model the flow rate of hydrogen in and out of the electrolysis module, it is necessary to work on a mole basis. In writing a mole balance for the system, we can write a balance on hydrogen and oxygen. These balances would have the form,

$$[\text{moles accumulation}] = [\text{moles in}] - [\text{moles out}] \quad (5.3-30)$$

By dividing Equation 5.3-26 by the molecular weight of water we will get the moles of water entering the system, which is equal to the moles of hydrogen and twice the moles of oxygen. The expressions become

$$q_{H2, in} = \frac{\pi (P_{tank} - P_{elec}) r^4 \rho_{H2O}}{(18) 8 u_{H2O} L} \quad (5.3-31)$$

and

$$q_{O2, in} = \frac{(1/2) \pi (P_{tank} - P_{elec}) r^4 \rho_{H2O}}{(18) 8 u_{H2O} L}, \quad (5.3-32)$$

where

$q_{H2, in}$ = The moles of hydrogen into the electrolysis module (moles/sec).

$q_{O2, in}$ = The moles of oxygen into the electrolysis module (moles/sec)

We know that the mole of hydrogen and oxygen produced are dependent on the electrolysis rate (5.3-3) given as

$$q = I/F, \quad (5.3-3)$$

where

q = Kmols of gas produced (Kmols/sec),

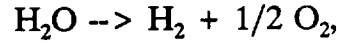
I = The current supplied to the electrodes (amp/sec),

F = Faraday's constant (9.6487×10^4 amp/equiv).

The moles of hydrogen produced can be written as

$$Q_{H_2, out} = \frac{I (amps)}{(9.6487 \cdot 10^4 amp/eqv.) (2 eqv. H_2/mole)}, \quad (5.3-34)$$

where hydrogen has 2 equivalents per mole. According to the reaction stoichiometry,



the moles of oxygen produced are half the moles of hydrogen produced. Therefore, one can write

$$Q_{H_2, out} = 1/2 Q_{O_2, out} \quad (5.3-35)$$

Now if we assume that the accumulation term in Equation 5.3-30 is equal to zero, we can determine the flow of water into the electrolysis module for a given current and find the pressure drop from the tank to the electrolysis module.

To determine the change in temperature in the electrolysis module, an energy balance needs to be made. This energy balance will be the same as the energy balances before except the energy put into the system by the electrodes need to be included. This energy balance can be written as

$$\begin{aligned} Cp_{avg} V_{E1} \rho_{avg} dT_{H_2O} - W_{H_2O, in} Cp_{H_2O} (T_{H_2O, in} - T_{ref}) \\ - Q_{H_2, out} (2) Cp_{H_2} (T_{H_2} - T_{ref}) \\ - Q_{O_2, out} (32) Cp_{O_2} (T_{O_2} - T_{ref}) \\ - Q_{cond, E2} - Q_{rad, E2} \\ + E_{elec} W_{H_2O, in} \\ + (H_{rxn}) \end{aligned} \quad (5.3-36)$$

The following definitions are required:

- $T_{H_2O, in}$ = temperature of water into the compartment (K).
- T_{H_2} = temperature of hydrogen out of the compartment (K).
- T_{O_2} = temperature of oxygen out of the compartment (K).
- ρ_{avg} = average density of the three gases (Kg/m³).
- Cp_{avg} = average heat capacity of the gas (K).
- Cp_{H_2} = heat capacity of hydrogen (KJ/Kg K).
- Cp_{O_2} = heat capacity of oxygen (KJ/Kg K).
- $Q_{cond, E2}$ = heat loss by conduction (KJ/sec).
- $Q_{rad, E2}$ = heat loss by radiation (KJ/sec).
- E_{elec} = electrical energy add to the system by the electrodes (KJ/Kg).
- H_{rxn} = the chemical energy added to the system due to the heat of reaction.

The heat loss by conduction through the tank walls can be expressed as (5.3-1)

$$Q_{cond, E2} = A_{E2} \left[\frac{1}{r_{E2} h_{H2}} + \frac{1 \ln r_{E3}/r_{E2}}{K_T} + \frac{1}{r_{E3} h_{surr}} \right]^{-1} (T_{H2} - T_{surr}) \quad 5.3-37$$

where

r_{E2} = inside radius of the electrolysis module (m).
 r_{E3} = outside radius of the electrolysis module (m).
 A_{E2} = surface area of the electrolysis module,
 excluding the side with the membrane (m²).

The heat loss due to radiation from the tank can be written as (5.3-1)

$$Q_{rad, E2} = A_{E2} \sigma (e_{E2} T_{H2}^4 - a_{E2} T_{surr}^4) \quad (5.3-38)$$

where

e_{E2} = the emissivity of the electrolysis module.
 a_{E2} = the absorptivity of the electrolysis module.

The energy added to the system by the electrodes can be written as (5.3-2)

$$E_{elec} = \frac{((2973 \text{ V/I}) + E_p) M_w}{(M_w + M_v) 2.7878 \times 10^{-4}} \quad (5.3-39)$$

with the following definitions:

E_p = "the non-electrolytic 'parasitic' energy used by
 the electrolyzer per kilogram of water converted
 to gas"(5.3-2),
 V = cell voltage,
 I = electrolyzer current efficiency,
 M_w = mass of water electrolyzed to gas (Kg),
 M_v = mass of water leaving the system (Kg).

The value of E_p is usually less than 0.05% of the total energy, and is therefore negligible. The M_v term is a function of temperature and pressure and is essentially constant at the temperature and pressure of interest, that is, a negligible amount of water vapor leaves the system with the product gases. Equation 5.3-39 can then be written as

$$E_{elec} = 10702 \text{ V/I} \quad 5.3-40$$

The chemical energy added to the system due to the heat of reaction can be written as (5.3-4)

$$H_{\text{rxn}} = M \sum (H^\circ - H^\circ_o + \Delta H_{f\ o}^\circ)_{\text{products}} - M \sum (H^\circ - H^\circ_o + \Delta H_{f\ o}^\circ)_{\text{reactant}}, \quad 5.3-41$$

where $H^\circ - H^\circ_o$ is the enthalpy of the element at 298K and the system temperature, respectively (KJ/mole) and $\Delta H_{f\ o}^\circ$ is the heat of formation of the compound from its elements.

Equations 5.3-37, 5.3-38, 5.3-40, and 5.3-41 can be substituted back into Equation 5.3-36 to give the change in temperature in the electrolysis module with respect to time.

CONCLUSIONS

The next step is to take the equations derived above and save them on EASY5. To improve the equations, it would be necessary to obtain more information on the porous membrane, and the water tank. The next step in improving the model would be to include the valves.

A place where the OGA sub-system could be improved is in the way the water tank is filled. The tank is presently filled every three hour whether it is empty or not. A possible improvement would be to fill the tank when the volume of the water portion of the storage reaches a certain value. When the volume reaches this value, the valves switch and allow the tank to fill. Then when the volume reaches another value, the valves switch back, and water is again supplied to the electrolysis module.

APPENDIX A
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APPENDIX C ACRONYMS

ACRONYMS

ACS	Atmosphere Control and Supply
AR	Atmosphere Revitalization
CMI	Computer/Monitor Instrumentation
CRS	Carbon Dioxide Reduction
ECLSS	Environmental Control and Life Support System
EVA	Extra-Vehicular Activity
FCA	Fluids Control Assembly
FDS	Fire Detection and Suppression
GTA	Graduate Teaching Assistant
NASA	National Air and Space Administration
OGA	Oxygen Generation Assembly
PCA	Pressure Control Assembly
SSF	Space Station Freedom
TCCS	Trace Contaminant Control System
THC	Temperature and Humidity Control
USRA	University Space Research Administration
WM	Waste Management
WRM	Water Recovery and Management